TAMPERE UNIVERSITY OF TECHNOLOGY

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PREDICTIVE MODEL FOR THE CARBON DIOXIDE CONCENTRATION OF INDOOR SPACES IN SCHOOL BUILDINGS

Master of Science Thesis

Examiner: Professor Timo Kalema

Examiner and topic approved by the Council Meeting of the Faculty of Automation, Mechanical and Materials Engineering on June 6th, 2012.

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Maxime Viot

“On ne va jamais aussi loin que lorsqu’on ne sait pas où l’on va” C.Colomb
(We never go as far as when we don’t know where we go)

Abstract

TAMPERE UNIVERSITY OF TECHNOLOGY
Department of Mechanics and Design
VIOT, MAXIME: Predictive model for the carbon dioxide concentration of indoor spaces in school buildings.
Master of Science Thesis, 91 pages, 7 appendices (19 pages)
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Keywords: carbon dioxide, CO_2, predictive model, multi-room CO_2 concentration model, opening between neighboring rooms, indoor air conditions, learning spaces, school buildings.

The objective of this thesis was to establish a trustable predictive calculation model for the carbon dioxide concentration of the air in indoor spaces and especially in school buildings. The model had to take into account not only the rooms, but also the neighboring spaces such as other rooms or corridors. These interactions are included to the model by analyzing of the airflow between different indoor spaces. The purpose of the model was to use better all the indoor spaces of the buildings to guarantee healthy air conditions but also to reduce the total demand for mechanical ventilation to save energy.

At first, a wide review of the literature has been made on the indoor air conditions, the control of ventilations inside of buildings and the existing calculation models. This provided a global knowledge on the subject, especially the official standard requirements needed before starting to analyze the problem.

Secondly, the mathematical model to predict the concentration of carbon dioxide inside the rooms of the school buildings was created. A particular focus was made on studying the airflows through an opening between two rooms and through the opened windows. Also, human emissions of carbon dioxide have been carefully considered due to their important influence on the indoor air conditions.

Finally, the measurements have been conducted for different situations in order to make comparisons with the model's results. They showed that using the other ventilation possibilities given by the different rooms and the windows can reduce the needs for mechanical ventilation. It has also demonstrated the ability of the model to give realistic results which could be further used for a ventilation control strategy.

Résumé

TAMPERE UNIVERSITY OF TECHNOLOGY
Department of Mechanics and Design
VIOT, MAXIME: Modèle prédictif pour la concentration de dioxyde carbone dans les espaces intérieurs des bâtiments d'éducation.
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Examinateur: Professeur Timo Kalema
Mots clés: dioxyde de carbone, CO_2, modèle prédictif, concentration de CO_2 dans un espace multisalles, ouverture entre deux salles voisines, qualité de l'air intérieur, espaces d'apprentissage, bâtiments d'éducation.

L'objectif de cette étude était d'établir un modèle le calcul la concentration de dioxyde de carbone de l'air des espaces intérieurs, et plus spécialement des bâtiments d'éducation. Le modèle devait prendre en compte non seulement plusieurs salles, mais aussi leurs espaces adjacents. Ces échanges entre espaces passent par l'analyse des flux d'air entre différents espaces intérieurs. Le but du modèle était d'utiliser au mieux les espaces intérieurs des bâtiments pour garantir un air sain, mais aussi de réduire la demande totale en ventilation artificielle et donc économiser de l'énergie.

Premièrement, une revue générale de la littérature a été conduite autour de la qualité de l'air intérieur, du contrôle de la ventilation des bâtiments et des modèles existants. Cela a permis d'établir une connaissance large du sujet, et notamment des normes officielles qui étaient requises pour le début de l'analyse du problème.

Deuxièmement, le modèle mathématique calculant la concentration de dioxyde de carbone dans les salles des écoles a été établi. Une attention particulière a été portée sur l'étude des flux d'air à travers les ouvertures entre deux salles voisines, ainsi qu'au travers des fenêtres ouvertes. Les émissions humaines de dioxyde de carbone ont été évaluées avec précision en raison de leur forte influence sur la qualité de l'air.

Finalement, les mesures qui ont été conduites dans différentes situations avaient pour but de confronter le modèle avec la réalité. Elles ont montré que l'utilisation des possibilités de ventilation alternatives offertes par les différents espaces et les fenêtres peuvent réduire substantiellement les besoins en ventilation artificielle. Cela a aussi démontré la capacité du modèle à donner des résultats réalistes, qui pourraient ensuite être utilisés pour une stratégie de contrôle de la ventilation.

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Abbreviations and notation

A	Area of an opening [m^2]
A_{Du}	DuBois area [m^2]
AFNOR	French Association for Standardization
ANSI	American National Standard Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BMI	Body Mass Index [%]
C	Concentration of CO_2 in a room
C_d	Discharge coefficient
C_{equi}	Equilibrium concentration of CO_2 in a room
C_i	Initial concentration of CO_2 in the room
C_0	CO_2 concentration of the outside air
$C(i)$	Concentration of CO_2 in a room at the step i
CAV	Constant Air Volume
CO_2	Carbon dioxide
ε_V	Ventilation efficiency
g	Standard gravity [m/s^2]
G	Production rate of CO_2 in a room [dm^3/s]
H	Accessible height of an opening [m]
H_b	Body height of a person [m]
HVAC	Heating, ventilation, and air conditioning

i_{max}	The number of steps
ISO	International Standardization Organization
k	Characteristic coefficient for ventilation vents
M	Metabolic equivalent of task [met], 1met=4.184 kJ kg^{-1} h^{-1}
n	The air exchange rate in a room [s^{-1}]
N_p	The number of occupants in a room
O_2	Oxygen
ppm	Parts per million
Q	Airflow rate in a room [dm^3/s]
Q_{ij}	Airflow rate through an opening between the rooms i and j [dm^3/s]
Qp	Airflow rate per person [dm^3/s]
Q_w	Airflow rate through an open window [dm^3/s]
REHVA	Federation of European Heating, Ventilation and Air-Conditioning Associations
RQ	Respiratory quotient
SFS	Finnish Standards Association
t	Time [s]
t_f	Final time or time duration [s]
T	Temperature in a room [K]
τ	Time constant [s]
TLV	Threshold limit value
VAV	Variable Air Volume
VAV_OP	Variable Air Volume with Openings
V	Volume of the room
$\dot{V}_{CO_2}$	Volume rate of CO_2 produced by one person [dm^3/s]

$\dot{V}_{O_2}$	Volume rate of O_2 consumed by one person [dm^3/s]
WIREPAS	Wireless measurement system
W_b	Body weight of a person [kg]
Δp	Pressure difference [Pa]
Δt	Time step [s]
ΔT	Temperature difference [K]
ρ	Density of air [kg/m^3]

Some notation can have additional subscript such as number referring to the place, e.g. C_1 for the CO_2 concentration of the room 1, or letters to describe the value in a context, e.g. Δp_m for the measured pressure difference or $\tau_{th}$the time constant from the theoretical model. Nevertheless the main notation keeps the same meaning.

Some notations that are only extracted from the literature and that are not used as such in the work are not listed here.

1. Introduction

Education in Finland is a major concern, and a lot of effort is put into providing the best conditions for pupils, students, and teachers. Indoor conditions of learning spaces have significant influence on learning and teaching, and many researches are carried out on this field, not only in Finland, but all around the world. In addition, the wish for a better environment is closely connected to energy and costs savings. This can be expressed in the following problem: how can we have good indoor conditions and low energy consumption without excessively increasing the costs?

The Suomen Yliopistokiinteistöt (Finnish University Facilities), Schneider Electric and ISS Proko are associated in a wide research project on this problem which is entitled Future Learning Environments, Tulevaisuuden oppimisen tilat in Finnish. This included different sub study packages and one is given to the department of Mechanics and Design of Tampere University of Technology: Indoor Air Conditions in Learning Spaces. It is in this project that the present study has been required.

The aim of this thesis is to find a good theoretical model to calculate the carbon dioxide (CO_2) concentration inside of a multi-room space in order to be able to predict the indoor air conditions. The model should include the possibility of having air exchange between the rooms and with the outside of the buildings via the windows. This model should also open the opportunity to build a control system for the mechanical ventilation air flow rates. It has to respect to air quality requirements and also has to control the mechanical ventilation flow rates to prevent excessive use of mechanical ventilation and to save energy.

Before anything else, a review of the literature had been done to gain knowledge about this subject. Especially the carbon dioxide as a gas and its effects on human health, but also the standard requirements for the air conditions from the different organizations have been studied, and also the different existing ventilation systems and their strategies to provide healthy indoor air conditions. Then the most important source of pollution in school buildings: the occupants and their emissions have been considered.

In the second phase, the mathematical model for the calculation of the CO_2 concentration inside of a multi-room space has been developed step by step. Different measurement sessions and tests have been conducted to compare the model with the real situations and to understand the needs better. Finally the control of the mechanical ventilation with the calculation model has been started and simulated.

2. Description of the Objects

2.1. Carbon Dioxide in General

Carbon dioxide is widely spread everywhere in our environment mainly as a gas. Nowadays CO_2 is a popular topic for media and politicians especially because of its part of responsibility in the global warming. Nevertheless CO_2 is contributing to allow life on earth in a specific ratio with the greenhouse effect where CO_2 is the most widespread of this kind of gases. But the global CO_2 concentration in the atmosphere increases due to human activities in particular and, even though it is not the only gas included in global warming process it the most common target which is why it is a hot topic. However CO_2 accountability in global warming is not the subject of this study, here I will focus on CO_2 as an air pollutant for indoor air comfort.

CO_2 is harmless for human health in most of the cases but CO_2 becomes toxic at high concentrations. The first effect to appear is a slight increase in the breathing depth over 1 % of CO_2 in the air (10 000 ppm). Then the respiratory volume rises by 30 % when air contains 2 % of CO_2 and next the breathing depth is doubled combined with an increase in the frequency of breathing over at 3 % of CO_2. Up to 5 % concentration breathing becomes difficult and uncomfortable and strong headaches may appear. Over 5 % of CO_2 in the air, an exposure of more than 30 minutes is enough to see signs of intoxication and mental depression appearing. Finally in environment containing over 10 % of CO_2 the conscious is lost after only a few minutes and can be fatal.

Carbon dioxide is emitted by any kind of burning processes, by organic decaying, by all living beings with digestive and respiratory process. This naturally includes humans, and for our concern, inside of learning spaces, they are the main if not the only source of CO_2 emission. Emitted by the respiration, CO_2 is present in the expired air at a ratio of about 4 %[1]. Thus CO_2 level of indoor air depends on the amount of people and follows the level of the other human effluents such as odors or moisture, which makes CO_2 being a good indicator for the indoor air quality. It means that when carbon dioxide level is at an acceptable concentration, other pollutants' levels in the air are also present in tolerable quantities.

(McIntyre, 1980)

[1] In the part 4.3 the human production of CO_2 is explained in details.

2.2. Effects of high CO_2 concentration indoors

As explained before, carbon dioxide can become toxic at high concentrations (over 10 000 ppm) but lower concentrations can also affect indoor comfort and thus the performance for achievement of any tasks. In the case of learning spaces, CO_2 concentration affects attention, concentration and memory, more generally on pupils' and students' performance. It inevitably affects teaching as well.

Many studies have been carried out lately about the effects of exposure to poor indoor air conditions and especially about CO_2. They all emphasize the link between these poor air conditions and diverse performance factors of students such as attention, absenteeism, reaction time, picture memory and many others. And this concern becomes bigger with the increase of air managing and building construction techniques.

A general review of the literature has been made by Mendell & Heath (2004) about the link of the indoor air conditions and the students' performances. The overview of this work emphasizes on the fact that even though quite little scientific evidence of high quality are available, many results are highlighting the effects of certain conditions with the performance and health of the pupils. They also found that these critical conditions are commonly found among the US schools visited by about 50 millions. This is of an even greater importance since the children are more susceptible to poor air conditions than adults. Indeed, their body is more active due to the growth and thus they breathe more air compared to their body weight. The article adds that in comparison to other kinds of buildings, schools are more likely to have poorer environments especially because of lack or inappropriate maintenance of buildings for economic reasons. Besides, after their home pupils spend most of their time in school. Adverse indoor conditions affecting students' performance can thus have consequences immediately and in the long term on their health and wellbeing and it could also have an effect on society.

(Mendell & Heath, 2004)

A study from Bakó-Biró et al. (2012) has monitored the effects of different ventilation rates on pupils' performance in schools in UK. They took measurements in eight schools, two in each season of the year, and used a mobile ventilation system to create changes in the normal air environment of classrooms. They used different basic tests on pupils: simple reaction time, choice reaction time, color word vigilance, addition reaction time, digit span memory, digit classification, digit-symbol matching, picture memory, and word recognition. Pupils were completing the tests when CO_2 had reached the steady level, usually before lunch break, every day of the week. From the results of the study an extreme case has been highlighted. Under the original indoor conditions, in one of the classrooms the CO_2 concentration has been measured at higher value than 5000 ppm at the end of a teaching session. They also report that the CO_2

sensors cannot handle more than 5000 ppm. These conditions inside the room are close to be over the limit of the health occupational value. A correlation between pupils' performance and indoor air has been emphasized in this study. The fastest and more accurate responses were obtained with the high ventilation rates and the differences were even more important for complex tasks. Also tiredness and loss of concentration were noticed in poor indoor conditions, remembering that the breathed air affects the brain via blood circulation within four seconds.

(Bakó-Biró et al., 2012)

2.3. Ventilation between neighboring rooms

The main idea of this study is to analyze the existing indoor conditions in learning spaces and to find new solutions to improve the indoor conditions and in this way the experienced indoor conditions and students' working performance. Thus understanding how these indoor conditions behave inside of learning spaces is a necessary first step, which starts with analyzing the behavior of a single room. But the real goal here is to improve the management of the ventilation system which means not consequently increasing the capacity of the ventilation system but trying to achieve this with the lowest mechanical ventilation capacity possible. How can this be done? A way is to take advantage of multi room spaces. Indeed in schools or universities, rooms are rarely all full at the same time, it might be often that a room is full when the neighboring room is empty or has a low occupancy. And for most of the rooms in educational buildings, lecture schedule is known in advance as well as the amount of students signed-in for these lectures. This can be used to predict the situation of CO_2 concentration in each room and to locate where an empty/low occupied room will be next to a full room. Thus I will try in this study to build a model for multi room spaces which will predict the CO_2 concentration by taking into account the occupancy and the air exchange between neighboring rooms. The plan is to use air exchange or air mixing between a low occupied and a fully occupied room (or more than two rooms) to lower the mechanical ventilation rate with respect of the maximum CO_2 concentration in each rooms.

3. Carbon dioxide concentration in rooms

3.1. Standard requirements

Indoor air conditions are regulated by different building regulations and standards which are established by different authorities and organizations in countries around the world where legislation can differ significantly. The main responsibility on the CO_2 concentration of indoor spaces belongs to national authorities, e.g. in Finland to the Ministry of environment. The Finnish legislation in the building regulation is called RakMk D2, Indoor air and ventilation.

The International Organization for Standardization (ISO) which has members in many countries, e.g. American National Standard Institute (ANSI) in USA, “Suomen Standardisoimisliitto” or Finnish Standards Association (SFS) in Finland, and “Association Française de Normalisation” or French Association for Standardization (AFNOR) in France. These organizations are trying to establish common standards which can then be recognized in all countries which agree. Some other organizations are specialized in ventilation such as the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), and in Europe the Federation of European Heating, Ventilation and Air-Conditioning Associations (REHVA). They use the international or local standards but are more adapted to the area and aimed to be used by the professionals. I will describe in this part the different standards and some useful indicators to describe the indoor air conditions.

3.1.1. Threshold limit value

A way to express the limits to the exposure to a gas or a pollutant, harmful or not is to use the Threshold Limit Value (TLV). The TLV as it has been defined by McIntyre (1980) is “*the maximum airborne concentration of a substance to which it is believed that nearly all workers may be repeatedly exposed day after day without adverse effect. Because of the wide variation of susceptibility between people, a small proportion of workers may experience discomfort from a substance at a concentration below the threshold limit.*” It is expressed here for workers but such limits can be established for school environments as well. Due to its industry origin the TLV is divided in three different values which express different types of exposure:

- TLV-Time Weighted Average (TLV-TWA) is the average concentration over an 8 hour workday or 40 hour working week, during which repeated exposure does not induce health issues.

- TLV-Short Term Exposure Limit (TLV-STEL) is the maximum concentration for a maximum of 15 minutes of exposure.
- TLV-Ceiling (TLV-C) is the maximum concentration that should never be exceeded no matter what.

From the previous list it is clear that TLV-STEL would not fit with any school situation but TLV-TWA and TLV-C are adapted to school schedules and environment.

(McIntyre, 1980)

3.1.2. Standard EN 15251

The standard EN 15251 “Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics” is defining and introducing many recommendations for the design of ventilation systems, energy calculation, inspection, evaluation and classification for a building’s indoor environment. In this study elements from this standard will be taken as references.

The environment classification extracted from the standard allows evaluating buildings according to four categories explained in the Table 3-1. These four categories are applicable for all the recommendations for indoor conditions which will follow.

Table 3-1 Description of the different indoor air categories (EN 15251)

Category	Explanation
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons
II	Normal level of expectation and should be used for new buildings and renovations
III	An acceptable, moderate level of expectation and may be used for existing buildings
IV	Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year

An index to classify the indoor air quality as a function of the CO_2 concentration or the required level of ventilation is defined in the Table 3-2. Ventilation level is based on health and comfort criteria and often meeting the comfort requirements will also meet the health criteria.

Table 3-2 Environment classification by CO_2 concentration (EN 15251)

Category	CO_2 concentration above the outdoor one [ppm]	Airflow per person [dm^3/s]
I	350	10
II	500	7
III	800	4
IV	>800	<4

In residential buildings, there has to be a minimum ventilation airflow rate during unoccupied periods for the building emissions of pollutants. The Table 3-3 from the standard gives the recommended values to apply depending on the type of the building. There are three types of buildings according to their emissions of pollutants. Buildings are low polluting or very low polluting when the majority of their materials are low polluting or very low polluting, and smoking is not or has never been allowed inside. Material's emissions of volatile organic compounds, formaldehyde, ammonia, carcinogenic compounds and odors have to be under certain levels to enter these categories[2]. The buildings which do not fulfill these two first categories are in the non-low polluting category. Otherwise, if no other value is given, an airflow rate between 0.05 and 0.1 $dm^3/(s\ m^2)$ should be applied.

Table 3-3 Recommended ventilation rates for building emissions (EN 15251)

Category	Airflow for building emissions pollutions [dm^3/s]		
	Very low polluting	Low polluting	Non low polluting
I	0,5	1	2
II	0,35	0,7	1,4
III	0,2	0,4	0,8

The standard also defines the temperature ranges for cooling during warm season and heating during cold season. The ranges are given to take into account for example the local customs or wishes for energy saving but the temperature within the day should not exceed these ranges. It can also allow occupants to adapt the temperature within these ranges. The table presenting the temperature ranges is given in appendix A. This table can here be used as an indicator for the possibility of opening windows for ventilation.

(EN 15251, 2007)

[2] The exact levels of those emissions of pollutants are described in the annex C of the standard EN ISO 15251: "Example on how to define low and very low polluting buildings".

3.1.3. Standard EN 13779

The standard EN 13779 "Ventilation for non-residential buildings – Performance requirements for ventilation and room-conditioning systems" gives recommendations for ventilation design in buildings, and especially for the positioning of inlet/outlet devices, definition of ventilation's performance, classification and design values. One relevant aspect for this work is the method of calculation of the appropriate supply volume flow rate in a room for a pollutant. It uses the allowed concentration level and the emission rate of this pollutant in the room in the equation (EN 13779):

$$q_{v,SUP} = \frac{q_{m,E}}{C_{IDA} - C_{SUP}} \qquad 3\text{-}1$$

Where:

- $q_{v,SUP}$ is the volume flow rate of supply air [m^3/s]
- $q_{m,E}$ is the mass flow rate of emission in the room [mg/s]
- C_{IDA} is the allowed concentration in the room [mg/m^3]
- C_{SUP} is the concentration in the supply air [mg/m^3]

It is also specified that in the case of several pollutants, the most relevant ones have to be considered and the most critical ones have to be used as reference for the determination of the ventilation flow rate.

(EN 13779, 2005)

3.1.4. Other recommendations about CO_2

The building bulletin 101 is giving some regulations and design guidance for ventilation of school buildings. About the maximum CO_2 concentration in any teaching or learning spaces, 1500 ppm should never be exceeded by the average value of the CO_2 concentration over the normal school hours. The ventilation system should have the capability to provide external air continuously at a minimum rate of 3 dm^3/s and per person for occupied spaces, but the system shall be capable of supplying 8 dm^3/s per person of outdoor air in order to maintain the CO_2 concentration under 1000 ppm.

(Building bulletin 101, 2005)

The American society ASHRAE is also giving requirements about the mechanical ventilation rates in occupied spaces. The recommended outdoor air supply rate is 20 cfm per person (i.e. 9.4 dm^3/s per person), and an occupant's density of 10 persons/1000 ft^2 maximum (i.e. 0.11 persons/m^2). It gives design values for the capability of the ventilation systems: they should be able to maintain the CO_2 concentration under the limit of 1000 ppm in the occupied spaces.

(ASHRAE, 1997)

3.2. Ventilation strategies

The main purpose of a building's ventilation system is to guarantee comfortable and healthy indoor air quality. In addition, it has to remove moisture from indoor spaces. The outdoor air supplied to the building will ensure people to have air to breath, remove excess pollutants and odors, and control the temperature and the level of humidity. Nowadays buildings are made more airtight and better insulated which means that the natural air exchange with outside air and the heat exchange are reduced. Moreover the standard requirements for indoor air condition, the ability to detect pollutants, the same time the knowledge of the effects of pollutants on health and the living standards have increased simultaneously. As a consequence, the mechanical ventilation flow rate requirements are increasing but it is also combined with the need to lower the energy consumption of buildings. Different types of ventilation strategies can provide good air conditions such as constant volume ventilation, demand controlled variable volume ventilation, or absorption of pollutants. In this study the CO_2 will be considered more specifically. And to obtain the best of the mechanical ventilation it therefore has to be efficient.

3.2.1. Efficiency of ventilation

The aim of ventilating a room is to maintain a good air quality inside the room for the occupants, thus the ventilation should be able to keep the contaminant levels under the required limits. Secondly the best ventilation system is the one which achieves this with the lowest outside air flow rate. On way to measure the ventilation effectiveness is to compare the different values of contaminant concentration at the inlet vent, exhaust vent, and the mean value.

This gives the following ratio for the efficiency of ventilation:

$$\varepsilon_V = \frac{C_e - C_s}{C_m - C_s} \qquad 3\text{-}2$$

where:

- C_e is contaminant concentration in exhaust, %
- C_s is contaminant concentration in the supply, %
- C_m is the mean concentration in the room, %

The efficiency of ventilation can take values larger or smaller than 1 depending on arrangement of the ventilation system inside the room, especially the supply and exhaust air vents. The efficiency of ventilation is equal to one when the air within the room is perfectly mixed; it means that the concentrations of all the pollutants are the same everywhere in the room. An example of this case is given on the Figure 3-1 where there is one air supply vent and two exhaust vents at opposite positions of the room.

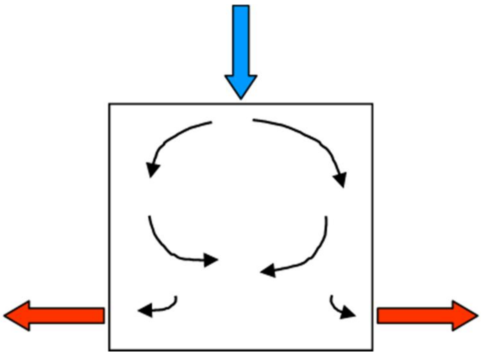

Figure 3-1 Example of mixing air ventilation

The efficiency of ventilation takes values greater than 1 when the exhaust concentration of pollutants is higher at the exhaust vent than the average concentration. It can happen if the exhaust is situated near the pollutant's source because the pollutant is removed before mixing with the air of the room. Another example is the displacement ventilation which is illustrated in the Figure 3-2, the flow of air moves in the room from only one side to the other, the concentration of pollutants gets the maximum value at the exhaust.

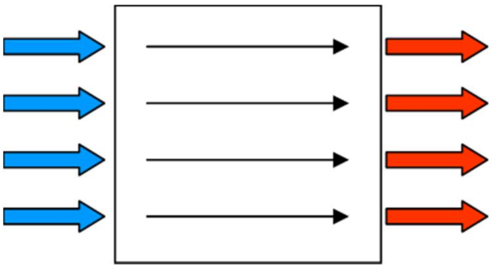

Figure 3-2 Example of displacement ventilation

The last possibility is to have efficiency of ventilation's value lower than 1. This situation happens when the vents in the room are not well positioned; it could create a loop in the air distribution and decrease the efficiency of the mechanical ventilation. It can be seen on the Figure 3-3 where the air supply and exhaust are placed so that a part of the supplied air is going out to the exhaust without mixing in the room and a part of the air is staying in the room. Such a bad configuration can even makes the ventilation system become ineffective.

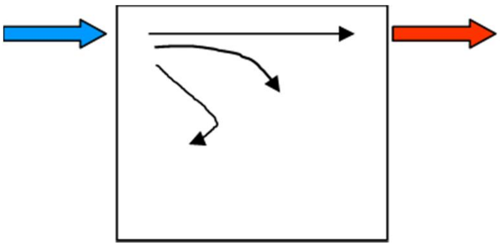

Figure 3-3 Example of loop in air distribution

(REHVA, 2010)

3.2.2. Constant air volume ventilation

The constant air volume ventilation is a simple way to provide new air inside a room or any space in order to satisfy the air condition requirements. The principle is very basic: the mechanical flow rate is defined by the less favorable use of the space for its air quality. In other words, when a space or a room is designed, it is for one or few specific purposes with a limit of occupants and the mechanical ventilation rate is calculated so that with the maximum amount of occupants doing the most pollutant activity, the different pollutant quantities in the room are under the limits. This rate is then assigned to the room and stays the same during the running period of the ventilation system. Constant air volume ventilation is thus inflexible and energy consuming strategy in case the use of the space changes during the time the ventilation is ‘on’.

3.2.3. CO_2 demand controlled variable air volume ventilation

The CO_2 demand controlled Variable Air Volume (VAV) ventilation is another strategy to provide good air conditions in indoor spaces. The principle is to measure the CO_2 concentration in the different rooms of the space and adjust the mechanical ventilation flow rates in each room according to their CO_2 concentrations. The maximum mechanical ventilation rates are calculated the same way as for the constant air volume ventilation, i.e. to keep pollutants’ level under the limits with the maximum pollution load expected in the room. An example of this strategy is given by Lu et al. (2011) for a sport training arena; the process of control is following these steps:

- Input CO_2 set point
- Fetch schedule information
- Read CO_2 level
- Estimate the number of occupants
- Calculate the minimum required outdoor ventilation rate
- Calculate the ventilation rate with measured CO_2 concentrations
- Set the ventilation rate as the maximum of the two possibilities

(Lu et al., 2011)

Another study from Nassif (2011) uses different scenarios for the CO_2 demand controlled ventilation in a multi-zone space. In the first scenario the number of occupants varies randomly and is not known, the ventilation rate is calculated from the design profile. The second scenario requires knowing the number of occupants in the whole space, the CO_2 concentration is measured from the exhaust ducts to adjust the ventilation rates by estimating the occupancy in the rooms. The latter strategy adjusts the mechanical ventilation flow rates in each room with the occupancy which needs to be known in each zone. The third option would have the biggest energy saving potential but it rare to know the exact occupancy everywhere in a building and the first scenario stays very close to the constant air volume ventilation. (Nassif, 2012)

The ideas from the two studies combined would probably give more realistic and energy saving potential to the strategy. Nevertheless another study case in Norwegian schools by Wachenfeldt (2007) has found that with CO_2 demand controlled variable volume ventilation the energy consumption of the air-handling unit can be reduced up to 87 % compared to constant air volume ventilation over a week's measurement period (Wachenfeldt, 2007).

3.2.4. Absorption of CO_2

Absorption of CO_2 in rooms is a specific alternative option to keep reasonable level of this pollutant in case of a peak in the concentration instead of increasing the mechanical ventilation rate. For instance the company Alfaintek Oy is offering a solution for CO_2 indoor absorption with its Uniqfresh CO_2 absorber. It is a reversible system which captures the CO_2 from the air by a chemical reaction when CO_2 is emitted in the room. The reaction then has to be done the other way to release the captured CO_2 during the unoccupied period. The release of the CO_2 gas is controlled so that the concentration in the room does not exceed the limit. The system also includes other filters for different pollutants such as dust, smoke, or odors to guarantee a good quality of the air released in the room. This absorber is available in different sizes and capacities from 80 to 400 l of CO_2 per cycle, and can be placed directly in the room with an electric supply. This solution of CO_2 removal is suitable for personal residences or low occupied spaces where the CO_2 concentration is reaching high levels only during short periods of time, and when the original mechanical ventilation system fulfills the need for air changing most of the time.

(Alfaintek Oy, 2012)

4. Human effect on indoor conditions

4.1. Metabolic Rate and Standard EN ISO 8996

The standard EN ISO 8996 “Ergonomics of the thermal environment – Determination of the metabolic rate” gives different methods to measure or estimate the metabolic rate depending on climate or working environment and energetic cost of specific work or sport activities, for example. For the present study, a definition of the metabolic rate and a correct estimate of its value according to activity will fulfill the needs. All the calculated values of the tables and given data of the standard are using as a reference the “average individual”:

- 70 kg and 1.75 m for a 30-years-old man
- 60 kg and 1.70 m for a 30-years-old woman

The metabolic rate is the energetic cost of muscular load for the conversion of chemical energy into mechanical and thermal energy. It also plays an important role in the level of comfort of an individual evolving in an environment. The useful mechanical work issued from the muscular activity is very low, about a few percent, and is neglected. The heat production is thus assumed to be the total energy consumed while doing an activity; therefore the metabolic rate is equal to the heat production rate.

There are different ways to determine the metabolic rate in practice, the Table 4-1 describes those methods classified in four levels from 1 to 4. In these levels, the accuracy of the results and the costs of the study are increasing also from 1 to 4. The level 1 is the simplest using tables for activities but the risk of error is rather big, the second level required observation of the working condition and table for more detailed body motion and work speed, but errors can still be high. The two last levels are giving much more accurate results (accuracy of more or less 10 and 5 % respectively) but require trained people to do specific measurements on the persons, heart beat rate for level 3 and indirect determination of the metabolic rate, and oxygen consumption, water turnover, or calorimetry for the direct metabolic rate determination in level 4.

Table 4-1 Levels for determination of the metabolic rate (EN ISO 8996)

Level	Method	Accuracy	Inspection of the work place
1 Screening	1A: classification according to occupation	Rough information Very great risk of error	Not necessary, but information needed on technical equipment, work organization
	1B: Classification according to activity		
2 Observation	2A: Group assessment tables	High error risk Accuracy: ± 20 %	Time and motion study necessary
	2B: Tables for specific activities		
3 Analysis	Heart rate measurement under defined conditions	Medium error risk Accuracy: ± 10 %	Study required to determine a representative period
4 Expertise	4A: Measurement of oxygen consumption	Errors within the limits of the accuracy of the measurement or of the time and motion study Accuracy: ± 5 %	Time and motion study necessary
	4B: Doubly labeled water method		Inspection of work place not necessary, but leisure activities must be evaluated
	4C: Direct calorimetry		Inspection of work place not necessary

The goal of this study is not to obtain an exact representation of the metabolic rate of students in learning spaces, the level 1 is thus enough to fulfill the need for the estimated value of the students' metabolic rates in classrooms. The Table 4-2 gives range values of metabolic rate by category of activities. In our case students in classrooms are situated in the low metabolic rate category with range value from 70 to 130 $W.m^{-2}$ or 1.2 to 2.2 met since 1 met, Metabolic Equivalent Task, is equal to 4.184 $kJ.kg^{-1}.h^{-1}$ or 58 $W.m^{-2}$. The standard also gives a value of 1.2 met for typical sedentary activity in offices, schools, dwellings, and laboratories.

(EN ISO 8996, 2004)

Table 4-2 Metabolic rate classified by category (EN ISO 8996)

Class	Average metabolic rate (with range in brackets)		Examples
	$W \cdot m^{-2}$	W	
0 Resting	65 (55 to 70)	115 (100 to 125)	Resting, sitting at ease
1 Low metabolic rate	100 (70 to 130)	180 (125 to 235)	Light manual work (writing, typing. drawing. sewing, book-keeping); hand and arm work (small bench tools, inspection, assembly or sorting of light materials); arm and leg work (driving vehicle in normal conditions, operating foot switch or pedal). Standing drilling (small parts); milling machine (small parts); coil winding; small armature winding; machining with low power tools; casual walking (speed up to 2,5 $km \cdot h^{-1}$).
2 Moderate metabolic rate	165 (130 to 200)	295 (235 to 360)	Sustained hand and arm work (hammering in nails, filing); arm and leg work (off-road operation of lorries, tractors or construction equipment); arm and trunk work (work with pneumatic hammer, tractor assembly, plastering, intermittent handling of moderately heavy material, weeding, hoeing, picking fruits or vegetables, pushing or pulling lightweight carts or wheelbarrows, walking at a speed of 2,5 $km \cdot h^{-1}$ to 5,5 $km \cdot h^{-1}$, forging).
3 High metabolic rate	230 (200 to 260)	415 (360 to 465)	Intense arm and trunk work; carrying heavy material; shovelling; sledgehammer work; sawing; planning or chiselling hard wood; hand mowing; digging; walking at a speed of 5,5 $km \cdot h^{-1}$ to 7 $km \cdot h^{-1}$. Pushing or pulling heavily loaded hand carts or wheelbarrows; chipping castings; concrete block laying.
4 Very high metabolic rate	290 (>260)	520 (>465)	Very intense activity at fast to maximum pace; working with an axe; intense shovelling or digging; climbing stairs, ramp or ladder; walking quickly with small steps; running; walking at a speed greater than 7 $km \cdot h^{-1}$.

4.2. Statistics of the population

The production carbon dioxide by human depends directly on the height and weight of people and their activity[3]. It is thus important to have well-estimated average values of height, weight and activity of the occupants of the room which will be analyzed. Here will be given data about Finnish population which will be used for the experiments done in the university, and also data from French population to give an example of differences between places but there is no sense to list every country, it is just to show that this information have to be collected according to the place where the experiment is taking place.

First about France, a campaign of measurement of the population has been conducted in 2006 by the French Fashion Institute for the clothing industry. The Table 4-3 gives the average weight and height of an adult French man and woman according to regions.

[3] It is explained in details in the next parts 4.3 and 4.4

Table 4-3 Size of French population in 2006, extracted from Campagne Nationale de Mensuration (2006)

	Males		Females	
	Height (cm)	Mass (kg)	Height (cm)	Mass (kg)
North-East	176,4	78,9	163,1	63,8
South-East	175,7	77,4	162,4	64,1
Ile de France	175,5	76,9	162,5	61,3
West	175,1	76,8	162,1	61,1
Total	175,6	77,4	162,5	62,4

Then for Finland, a survey conducted by Helakorpi et al. (2011) from the National Institute for Health and Welfare about health behavior and health among the Finnish adult population gives information about the size of Finnish people. The extracted data about height and weight are presented in Table 4-4 below.

The bottom of the Table 4-4 gives the Body Mass Index[4] (BMI) and is directly extracted from Helakorpi et al. (2011) but the final row gives the average weight of Finnish students. These last values are obtained from the average height of students, the part of each age group in the student population and the BMI. In other words, BMI for the student column are calculated by averaging the BMI values of each age group taking into account the percentage of each group in the student population. Then the average BMI is the weighted average of all the BMI taking the median value of each BMI interval. And finally the average weight is obtained by the BMI formula. These average values of height and weight of Finnish students will be used to calculate the CO_2 emission of room's occupants in the experiments presented later.

[4] The Body Mass Index (BMI) is given in % and calculated by dividing the mass [kg] of a person by its height [m] squared, in the following equation: $BMI = \frac{W_b}{H_b^2}$

Table 4-4 Size of Finnish population in 2010, extracted from Helakorpi et al.(2011) and US Census Bureau (2012)

Finnish adult population		Males			Females		
		Age group			Age group		
		15-24	25-34	Total	15-24	25-34	Total
Part of age group in total population		13,0 %	13,4 %	26,4 %	11,9 %	11,9 %	23,8 %
Number of respondent		177	179	356	252	260	512
Number of student		124	15	139	199	28	227
Part of age group in total student respondent		89,2 %	10,8 %	-	87,7 %	12,3 %	-
Average Height [cm]							
Living area	Southern Finland	179	182	-	165	166	-
	Western Finland	180	181	-	167	166	-
	Middle Finland	178	178	-	166	167	-
	South-eastern Finland	181	180	-	166	164	-
	Eastern Finland	180	177	-	166	164	-
	Northern Finland	177	179	-	164	166	-
Status	Student	178	182	179	166	167	166
Year	2010	179	180	-	165	166	-
Body Mass Index [kg/m^2]				Student			Student
Group	14-19,99	18,0 %	5,1 %	16,6 %	27,7 %	15,0 %	26,1 %
	20-24,99	53,5 %	52,0 %	53,3 %	57,9 %	47,8 %	56,7 %
	25-29,99	22,7 %	32,2 %	23,7 %	9,9 %	23,7 %	11,6 %
	30-	5,8 %	10,7 %	6,3 %	4,5 %	13,4 %	5,6 %
Student Average BMI [kg/m^2]		23,4			22,2		
Student Average Weight [kg]		75,1			61,3		

4.3. Human breathing process

The production of CO_2 by the human breathing is linked to the consumption of oxygen during breathing moves. A brief description of how human's respiratory system works will be given here in order to understand globally the breathing process.

The respiratory system of human is described with the help of four different volumes and four capacities which are shown on the Figure 4-1. The tidal volume is the quantity of air inspired or expired during a normal breath; the inspiratory reserve volume is the extra volume of air that can be inspired over the tidal volume during a full force inspiration. Other pulmonary volumes includes the expiratory reserve which is the maximal volume that can be expired with full force after a normal expiration from the tidal volume, and the residual volume which is the remaining air volume in the lungs after the maximal expiration. All together these volumes form the total lung capacity which is the maximum volume of air that the lungs can contain. Then the vital capacity equals the expiratory reserve plus the inspiratory reserve and the tidal volume, it is the maximum usable volume of breath. The inspiratory and functional residual capacities are respectively the amounts of air one can breathe in starting from the normal expiratory level and the remaining amount of air at the end of a normal expiration. The Table 4-5 gives the typical values of these volumes and capacities for a young adult man, for women they are usually about 20 to 25 percent less but they can be also greater for large and athletic people. For the people activity considered in this study the tidal volume will be the volume to take into account.

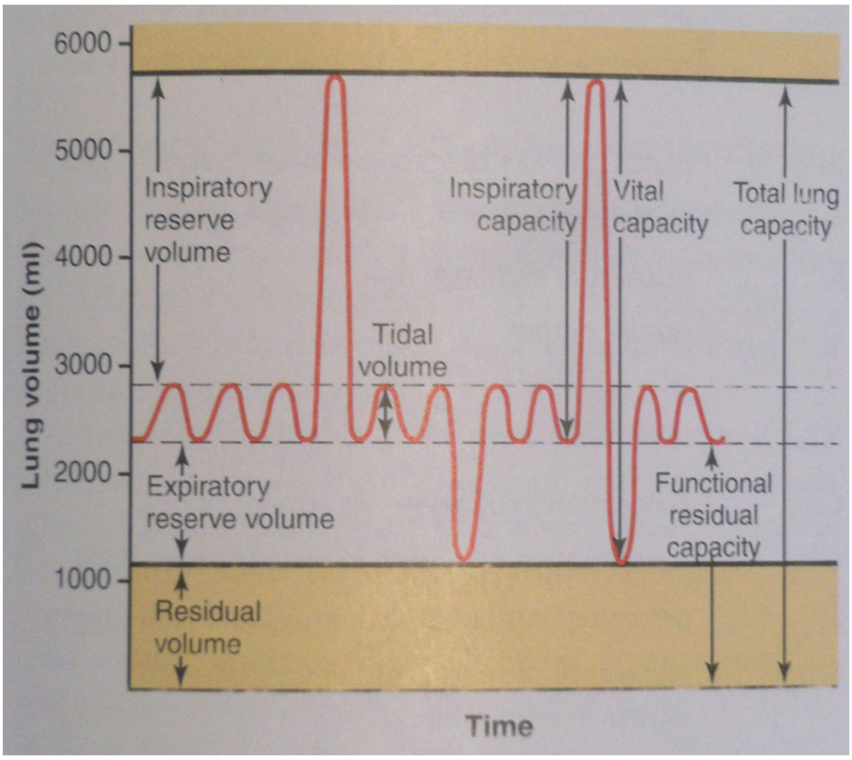

Figure 4-1 Human's lung volumes and capacities, extracted from Hall (2011)

Table 4-5 Pulmonary volumes and capacities for a young adult man (Hall, 2011)

Pulmonary volumes and capacities		Volume [dm^3]
Tidal volume	1	0,5
Inspiratory reserve volume	2	3,0
Expiratory reserve volume	3	1,1
Residual volume	4	1,2
Inspiratory capacity	1 + 2	3,5
Functional residual capacity	3 + 4	2,3
Vital capacity	1 + 2 + 3	4,6
Total lung capacity	1+ 2 + 3 + 4	5,8

To obtain the breathing rate of people called the minute respiratory volume it is needed to know the frequency of their breathing moves. This minute respiratory volume is the total amount of air flowing in the respiratory system during one minute; it is given by multiplying the respiratory rate per minute by the tidal volume. This volume can vary from 1.5 l/min (2 to 4 breaths per minute) to 200 l/min or even greater when the tidal volume equals the vital capacity and a respiratory rate of 40 to 50 per minute. The normal value for the minute respiratory volume is about 6 l/min with 12 breaths per minute and with a tidal volume of 0.5 l. During a breath move not all the new fresh air reaches the lungs a part of this volume stays in the air passageways where no gas exchange occurs; this volume is called dead space and is about 0.15 l. Thus the real functional volume of the gas exchange capacity for each breath move is the tidal volume minus dead space: 0.35 l per breath and 4.2 l/min for the normal respiratory rate.

(Hall, 2011).

4.4. CO_2 emissions and human model

The link between the consumption of oxygen and the CO_2 emission is the respiratory quotient (RQ). This ratio is the rate of oxygen (O_2) used and transformed into carbon dioxide when humans are breathing. Its value varies between 0.7 and 1 but the normal value for moderate activity and normal diet is 0.82 (McIntyre, 1980) or 0.83 (REHVA, 2010). That gives the following equation to link the two volume rates:

$$\dot{V}_{CO_2} = \mathrm{RQ}.\dot{V}_{O_2} \qquad \text{4-1}$$

Table 4-6 Oxygen consumption depending on the task (ASHRAE, 1989)

Level of exertion	Oxygen consumed (l/min)
Light work	<0,5
Moderate work	0,5 – 1,0
Heavy work	1,0 – 1,5
Very heavy work	1,5 – 2,0
Extremely heavy work	>2,0

The volume rate of O_2 consumption depends on the level of activity or metabolic rate (M) of the person and the size of this person via the body surface area. As an indicator the Table 4-6 gives average values of oxygen consumption for different levels of exercise and for a normal adult man. For more precise values the DuBois area, A_{Du} [m^2], gives an estimation of this body surface area based on the weight and the height of a person. It is defined by the equation:

$$A_{Du} = 0{,}202 W_b^{0{,}425} H_b^{0{,}725} \qquad \text{4-2}$$

where:

- W_b is body mass [kg]
- H_b is body height [m]

And with RQ the respiratory quotient and M the metabolic rate introduced before the oxygen consumption of a person [dm^3/s] is given by the equation:

$$\dot{V}_{O_2} = \frac{0{,}00276 A_{Du} M}{0{,}23 RQ + 0{,}77} \quad \text{4-3}$$

From the previous equations 4-1 and 4-3 we can establish the equation for the CO_2 emission of one person [dm^3/s]:

$$\dot{V}_{CO_2} = RQ.\frac{0{,}00276 A_{Du} M}{0{,}23 RQ + 0{,}77} \quad \text{4-4}$$

(REHVA, 2010).

Another approach from McIntyre (1980) is to use the metabolic energy liberated from the consumption of one liter of oxygen which is equal to $20{,}2 \times 10^3$ J for a normal diet. The rate of carbon dioxide produced by a person [dm^3/s] can therefore be expressed in function of the metabolic rate expressed in [W/m^2][5]:

$$\dot{V}_{CO_2} = \frac{\mathrm{RQ}}{20{,}2.10^3} M A_{Du} \quad \text{4-5}$$

Where:

- M is the metabolic rate [W/ m^2]
- A_{Du} is the DuBois area [m^2]
- RQ is the respiratory quotient

(McIntyre, 1980)

These two equations are giving very close results for the estimation of human emission of CO_2, for example for an average Finnish student:

- Height = 1.725 m
- Weight = 68.2 kg
- RQ = 0.83
- M = 1.2 met (1 met = 58.0 W/m^2 → M = 69.6 W/m^2)

[5] 1 met = 58 W/m^2

Thus A_{Du} = 1.80 m^2 and with the REHVA's equation $\dot{V}_{CO_2}$ = 5.1626x10^{-3} dm^3/s and with McIntyre's equation $\dot{V}_{CO_2}$ = 5.1608x10^{-3} dm^3/s but if we consider the significant number of digits both give $\dot{V}_{CO_2}$ = 5.16x10^{-3} dm^3/s. Therefore either the first or the second equation can be used for the calculation of human's CO_2 emissions.

The influence of occupancy of rooms being the main source of carbon dioxide for school buildings the emission rate of one person has to be evaluated carefully. Therefore the equation 4-4 from REHVA (2010), to calculate this human emission rate, will be used in the calculation model for the CO_2 concentrations presented in the next parts. In the calculation via Matlab these equations will be included in a common script used then by Matlab calculation scripts. This script for human CO_2 emission rate is given in detail in the Programme 4-1 using the data on Finnish students. When running this script with Matlab it gives a CO_2 emission rate per person of $\dot{V}_{CO_2}$ = 5.16x10^{-3} dm^3/s. For the modeling via Excel, the human CO_2 emission rate is calculated and used as a constant value. The equations are depending on people size and activity, thus the official data on Finnish population for Finland is used in this study for all the calculations which will be presented after. If the calculation is made for a building in another region, it would be necessary to obtain the right data and replace them in the inputs of the model.

```
%--------------------------Human metabolism--------------------------
%REHVA Model

%Height [m]
Hb=1.725; %Average height of Finnsih student (15-34y)

%Weight [kg]
Wb=68.2; %Average weight of Finnsih student (15-34y)

%DuBois area [m2]
Adu=0.202*Wb^0.425*Hb^0.725;

%Respiratory quotient
RQ=0.83;

%Metabolic rate [met]
M=1.2;

%CO2 emission per person [dm3/s]
global Vco2;
Vco2=RQ*0.00276*Adu*M/(0.23*RQ+0.77);
```

Programme 4-1 Matlab script for human emission of CO_2

5. Predictive CO_2 concentration model

5.1. Calculation of CO_2 concentration in a classroom

In the previous chapter was described the human production of CO_2, and that it is the main source of CO_2 indoors. The CO_2 present in the outdoor air, about 380 ppm nowadays, has to been taken into account. The concentration in an indoor environment can vary from 500 ppm to 5000 ppm and can also come from any other devices where combustion processes are occurring.

In a single room space there is gas exchange with outdoor air, a carbon dioxide source, an air purifier device and possible absorption of carbon dioxide by walls or other furniture in the room. The evolution of the concentration of carbon dioxide in the room is given by the following differential equation:

$$\frac{dC}{dt} = \frac{G}{V} + nC_o - nC(t) - \frac{v_d S}{V} - \frac{Q_{ac}}{V} C\varepsilon_{ac} \qquad \text{5-1}$$

Where:

- C is the concentration of CO_2 of indoor spaces [mg/m^3]
- G is the CO_2 production inside the room [mg/h]
- V is the volume of the room [m^3]
- n is the air exchange rate, i.e. the outdoor air flow rate divided by the volume of the room [h^{-1}]
- C_o is the CO_2 concentration of outside or supply air [mg/m^3]
- v_d is the rate of absorption of the CO_2 [mg/(hm^2)]
- S is the area of absorption [m^2]
- Q_{ac} is the flow rate through the CO_2 absorber [m^3/h]
- ε_{ac} is the efficiency of the CO_2 absorber

The production of CO_2 in a room in case of learning spaces is coming from the N_p students present and is given by the following equation:

$$G = \dot{V}_{CO_2} N_p \qquad \text{5-2}$$

The model can be simplified if there is no absorption of CO_2 at all and no CO_2 absorber in the room, or these effects could also be subtracted to the inside CO_2 production rate to have only one CO_2 factor G. The differential equation becomes:

$$\frac{dC}{dt} = \frac{G}{V} + \mathrm{n}\big(C_o - C(t)\big) \qquad 5\text{-}3$$

Assuming that the volume of the room, the air exchange rate, the outside air CO_2 concentration, and the inside CO_2 emissions are constant, taking C_i as the initial CO_2 concentration in the room at t = 0, the solution to the equation 5-3 for the interior CO_2 is:

$$C(t) = C_o + \frac{G}{Q} + (C_i - C_o - \frac{G}{Q})e^{-nt} \qquad 5\text{-}4$$

In this case the equilibrium concentration in the room can be calculated to simplify the solution to the equation 5-3 with the outdoor concentration C_o and the outdoor air flow $Q = nV$:

$$C_{equi} = C_o + \frac{G}{Q} = C_o + \frac{G}{nV} \; [mg/m^3] \qquad 5\text{-}5$$

Equation 5-5 replaced in equation 5-4:

$$C(t) = C_{equi} + \big(C_{\mathrm{i}} - C_{equi}\big)e^{-nt} \qquad 5\text{-}6$$

(REHVA, 2010)(Lu T. et al., 2011)(Zeiler et al., 2009)

5.2. Single room CO_2 model

In order to be able to build the model of a multi-room space it is needed to start by one isolated room and to make an accurate model of its CO_2 concentration evolution. Starting from the existing equations from the literature described in the previous part, there are two solutions to the differential equation of the CO_2 balance in the room: analytical and numerical.

The differential equation used is:

$$\frac{dC}{dt} = \frac{G}{V} + nC_o - nC(t) \qquad 5\text{-}7$$

With:

$$n = \frac{Q}{V} \qquad 5\text{-}8$$

And where:

- C is the concentration of CO_2 in the room as a function of time
- C_o is the outdoor concentration of CO_2
- G is the production of CO_2 inside the room [dm^3/s]
- V is the volume of the room [dm^3]
- Q is the air inflow rate [dm^3/s]
- n is the air change rate [s^{-1}]

The first solution to the equation 5-7 is analytical, and similar to the one from the literature presented before. Only units have been change to be closer to the one commonly used for ventilation flow descriptions which is [l/s] or [dm^3/s] in SI unit system. The result has to be then multiplied by 10^6 to obtain the concentration in [ppm]. The analytical solution with C_i as the initial concentration of CO_2 in the room is:

$$C(t) = C_o + \frac{G}{Q} + (C_i - C_o - \frac{G}{Q})e^{-nt} \quad 5\text{-}9$$

The second solution to the equation 5-7 is a numerical solution obtained by the finite difference method. The equation here is an ordinary differential equation, the Euler method can be used for the function $C(t)$. This method uses the finite difference approximation to replace the derivative. And the approximation comes from the Taylor's polynomial which for a function $f(x)$in x_0 is:

$$f(x_0 + h) = f(x_0) + \frac{f'(x_0)}{1!}h + \frac{f^{(2)}(x_0)}{2!}h^2 + \cdots + \frac{f^{(n)}(x_0)}{n!}h^n + R_n(x) \quad 5\text{-}10$$

Taking only the first derivative of the function f:

$$f(x_0 + h) = f(x_0) + f'(x_0)h + R_1(x) \quad 5\text{-}11$$

Solving for the derivative:

$$f'(x_0) = \frac{f(x_0+h)-f(x_0)}{h} - \frac{R_1(x)}{h} \quad 5\text{-}12$$

And with $R_1(x)$ sufficiently small:

$$f'(x_0) \approx \frac{f(x_0+h)-f(x_0)}{h} \quad 5\text{-}13$$

Thus using the equation 5-13 for the function of the CO_2 concentration gives:

$$\frac{dC}{dt} \approx \frac{C(t+\Delta t)-C(t)}{\Delta t} \quad 5\text{-}14$$

Replacing in equation 5-7:

$$\frac{C(t+\Delta t)-C(t)}{\Delta t} = \frac{G}{V} + nC_o - nC(t) \quad 5\text{-}15$$

This finally gives the numerical solution to equation 5-7:

$$C(t + \Delta t) = C(t) + \Delta t\left(\frac{G}{V} + nC_o - nC(t)\right) \quad 5\text{-}16$$

This solution can then be implemented with a step by step calculation. The step size is Δt and indices can be used, the value of the concentration at the step i represents $C(t + \Delta t)$ and the previous value at the step i-1 represents $C(t)$. This gives the following equation with the initial condition:

$$\begin{cases} C(0) = C_i \\ C(i) = C(i_{-1}) + \Delta t\left(\frac{G}{V} + n\left(C_o - C(i_{-1})\right)\right) \end{cases} \qquad 5\text{-}17$$

With:

$$\Delta t = \frac{t_f}{i_{max}} \qquad 5\text{-}18$$

And where:

- t_f is the final time for calculation or duration [s]
- i_{max} is the number of steps
- Δt is the time step for calculation [s]
- $C(i) and\, C(i-1)$ are the concentrations of CO_2 at the step i and i-1

The inputs used for both solutions are the size of the room (height, width, and length), the inflow rate, the length of the time period for the calculation, the occupancy of the room, and the occupants' characteristics. In order to determine a coherent time step for the numerical solution the time constant of the analytical solution has to be calculated:

$$\tau = 1/n \qquad 5\text{-}19$$

For numerical solution to first order differential equation the time step Δt and the length of the calculation period t_f have follow the following rules:

$$\begin{cases} \Delta t < \tau/10 \\ t_f > 5\tau \end{cases} \qquad 5\text{-}20$$

Using Matlab scripts given in the appendix B, the two solutions can be compared. For this comparison the room's size is 8 x 9 x 3 m, there are 25 Finnish students inside, the air supply rate is 180 dm^3/s, the supply air CO_2 concentration is 410 ppm (measured in an inlet vent of the university), the initial CO_2 concentration is 410 ppm, and the calculation period is 120 min long. The time constant here is:

$$\tau = \frac{1}{n} = \frac{V}{Q} = \frac{216000}{180} = 1200\,s = 20\,min \qquad 5\text{-}21$$

The length of the period is 120 min which is more than $5\tau = 100\,min$ and the time step is equal to 2 min (equals to $\tau/10$) for the numerical solution. The Figure 5-1 shows the plotted result of the calculation of both analytical and numerical solutions to the equation 5-7. In the Figure 5-1 is also given the CO_2 concentration at $t = \tau$ for the numerical solution, $C_{num}(\tau)$ = 877 ppm. From the analytical solution this value is a characteristic value to determine the time constant, i.e. at $t = \tau$ the CO_2 concentration reaches 63.2 % of its final value, $C_{th}(\tau)$ = 863 ppm (the final value is calculated with equation 5-5 and is 1127 ppm). Thus the relative error at $t = \tau$ is about 1.6 % and on the Figure 5-1 can also be noticed that the two solutions converge into the same final value. These results are therefore giving the confirmation that the two solutions are equivalent with a correct time step for the numerical one.

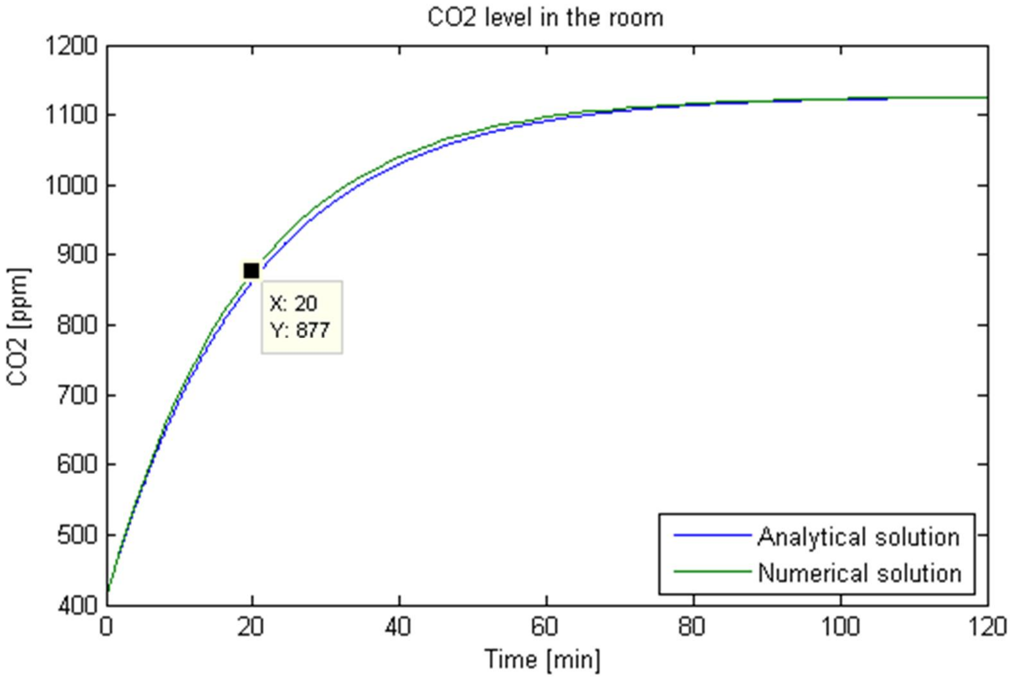

Figure 5-1 Comparison of analytical and numerical solution for single room CO_2 concentration model

The numerical solution is chosen in this modeling because it offers more flexibility to cope with real situations. Indeed, with the analytical solution it is not possible to have a variable occupancy over the calculation's time period. And occupancy in a room might change over a day depending on lessons and also during breaks, this change would be even more rapid and random for a free-access room. Therefore with the numerical solution it is possible to update the number of occupants and thus the CO_2 emission in the room for each step by giving the occupancy as a function of time.

5.3. Multi-room CO_2 model

Now, having presented and defined clearly the evolution of the CO_2 concentration in an isolated room, it needs to be extended to a space with at least two rooms where the possibility to have air exchange between two neighboring rooms is given. Such a model could be done for an entire building with many rooms but the idea here is to give the principle of this approach of the "multi-room space". Thus I will use here a configuration with three rooms and one corridor which is a configuration commonly seen in school buildings where one room, like in the Figure 5-2, has most of the time one wall with windows for natural light and ventilation, one wall with the corridor, and two walls with other rooms. It can also have two walls with outside or with corridor but one room has almost always wall connection with outside, corridor and one other room.

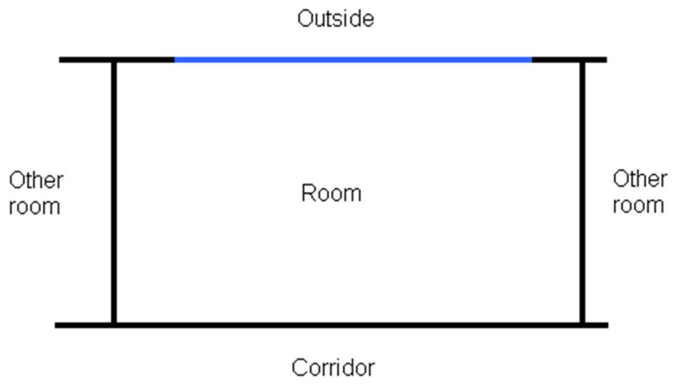

Figure 5-2 Schematic view of a room's wall connections

5.3.1. Simplified multi-room space for the CO_2 model

Building the complete multi-room CO_2 model requires taking into account all the numerous parameters, it is thus easier to start with a simplified depiction of the space and then include all the parameters. The first step was to determine the equations of the CO_2 concentration for each room with the simplified multi-room space described in the Figure 5-3. Each room has its own volume (e.g. V1 for room 1), occupancy (e.g. Np1 for room 1), air inflow (e.g. Q1 in blue for room 1), and the same rate for the air outflow in red. And between each room there are air exhanges Qex, i.e. that the flow rate going from room 1 to 2 is equal to Qex and the airflow from room 2 to 1 is also Qex, and it is the same for each room to room air exchange.

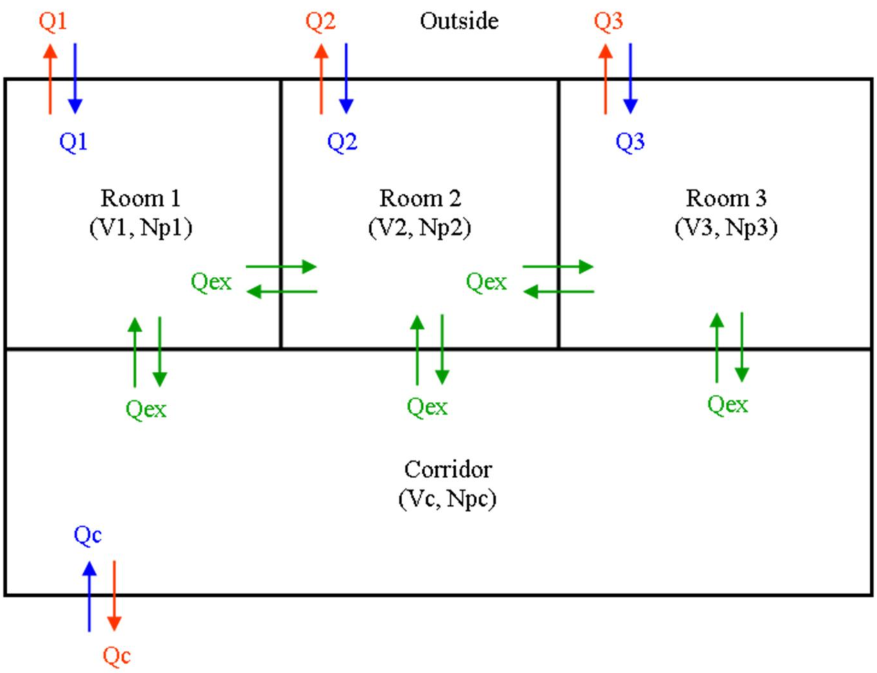

Figure 5-3 Simplified multi-room space characteristics

To calculate the concentration of CO_2 in each room, a system of four differential equations is required. The equations are connected between each other because of the air exchange between rooms. The system is:

$$\begin{cases} \frac{dC_1}{dt}=\frac{G_1}{V_1}+n_1C_o+\frac{Q_{ex}}{V_1}\left(C_2(t)+C_c(t)\right)-n_1C_1(t)-\frac{2Q_{ex}}{V_1}C_1(t) \\ \frac{dC_2}{dt}=\frac{G_2}{V_2}+n_2C_o+\frac{Q_{ex}}{V_2}\left(C_1(t)+C_{3(t)}+C_c(t)\right)-n_2C_2(t)-\frac{3Q_{ex}}{V_2}C_2(t) \\ \frac{dC_3}{dt}=\frac{G_3}{V_3}+n_3C_o+\frac{Q_{ex}}{V_3}\left(C_2(t)+C_c(t)\right)-n_3C_3(t)-\frac{2Q_{ex}}{V_3}C_3(t) \\ \frac{dC_c}{dt}=n_cC_o+\frac{Q_{ex}}{V_c}\left(C_1(t)+C_2(t)+C_3(t)\right)-n_cC_c(t)-\frac{3Q_{ex}}{V_c}C_c(t) \end{cases} \quad 5\text{-}22$$

with:

$$n_i=\frac{Q_i}{V_i} \quad 5\text{-}23$$

and where:

- C_1, C_2, C_3, C_c are the CO_2 concentrations in rooms 1, 2, 3 , and corridor
- G_1, G_2, G_3 are the CO_2 productions in rooms 1, 2, and 3 [dm^3/s]
- V_1, V_2, V_3, V_c are the volumes of rooms 1, 2, 3, and corridor [dm^3]
- Q_1, Q_2, Q_3, Q_c are the air inflow rates in rooms 1, 2, 3, and corridor [dm^3/s]
- n_1, n_2, n_3, n_c are the air change rates of rooms 1, 2, 3, and corridor [s^{-1}]
- Q_{ex} is the air exchange between neighboring rooms [dm^3/s]

Again like for the single room equation, this system can have two different solutions: analytical and numerical. Solving the system to get the analytical solution would be long and tedious, but this solution can be approximated with non-linear numerical method on Matlab. To do so Matlab has different solving functions. For this simplified step only the numerical solution has been developed because the aim of this simplification was first to establish equations for a multi-room space. The two solutions will be presented on the other hand in the end of this part for the full multi-room space model. Nevertheless the numerical solution to the equation system 5-22, obtained from the finite difference method is:

$$\begin{cases} C_1(i)=C_1(i_{-1})+\Delta t\left(\frac{G_1}{V_1}+n_1C_o+\frac{Q_{ex}}{V_1}\left(C_2(i_{-1})+C_c(i_{-1})\right)-\left(n_1+\frac{2Q_{ex}}{V_1}\right)C_1(i_{-1})\right) \\ C_2(i)=C_2(i_{-1})+\Delta t(\frac{G_2}{V_2}+n_2C_o+\frac{Q_{ex}}{V_2}(C_1(i_{-1})+C_3(i_{-1})+C_c(i_{-1}))-\left(n_2+\frac{3Q_{ex}}{V_2}\right)C_2(i_{-1})) \\ C_3(i)=C_3(i_{-1})+\Delta t(\frac{G_3}{V_3}+n_3C_o+\frac{Q_{ex}}{V_3}(C_2(i_{-1})+C_c(i_{-1}))-\left(n_3+\frac{2Q_{ex}}{V_3}\right)C_3(i_{-1})) \\ C_c(i)=C_c(i_{-1})+\Delta t(n_cC_o+\frac{Q_{ex}}{V_c}(C_1(i_{-1})+C_2(i_{-1})+C_3(i_{-1}))-\left(n_c+\frac{3Q_{ex}}{V_c}\right)C_c(i_{-1})) \end{cases} \quad 5\text{-}24$$

with initial conditions in each room:

$$\begin{cases} C_1(0) = C_{i1} \\ C_2(0) = C_{i2} \\ C_3(0) = C_{i3} \\ C_c(0) = C_{ic} \end{cases} \tag{5-25}$$

This representation of the space is not complete enough to reach the objective of this work, thus two essential parameters and their respective equations will be introduced in the model. First a presentation of how to calculate the flow rate resulting from having an opening in the wall of two neighboring rooms. And next an explanation on how to calculate the flow rate from an opened window. Finally the equations for the CO_2 concentration model with all the parameters will be presented.

5.3.2. Flow between rooms

Using neighboring rooms to even the CO_2 concentration within the room considered and decrease the total mechanical ventilation rate is one of the main purposes of this project. Including it to a CO_2 concentration model will be new and will give all the value to the results of this work. Thus establishing the equation of the air flow through an opening between two rooms is important.

The value of the flow through an opening can be calculated from the equation:

$$Q_{ij} = C_d A \sqrt{\frac{2\Delta p}{\rho}} \tag{5-26}$$

where:

- Q_{ij} is the flow rate across the opening between rooms i and j [m^3/s]
- C_d is the discharge coefficient [no unit]
- A is the area of the opening [m^2]
- ρ is the density of air [kg/m^3]
- Δp is the pressure difference through the opening [Pa]

Here the discharge coefficient cannot be calculated with any formula. This coefficient is determined by experimental measurements, it depends mainly on the type of opening and for openings into exterior air from the wind pressure and the wind direction. In the case of an indoor opening between two rooms there is no wind thus the discharge coefficient will be considered equal to 1, at first. The product of the area with the discharge coefficient is called the effective area.

For buoyancy driven flow, which is the case between two rooms if there is no fan, the pressure difference can be connected to the temperature difference. Indeed, inside, measuring the pressure difference between two rooms is more difficult than measuring the temperature difference. An equation using the temperature difference is thus more appropriate in this case.

For a small opening with buoyancy driven flow the pressure difference is:

$$\Delta p = -\rho g H \left(\frac{\Delta T}{T_i}\right) \quad 5\text{-}27$$

Where:

- g is the standard gravity and is equal to 9.81 m/s^2
- H is the accessible height of the opening [m]
- T_i is the inside temperature [K]
- ΔT is the temperature difference between the rooms [K]

Replacing equation 5-27 in equation 5-26 gives the new equation of the flow through the opening:

$$Q_{ij} = C_d A \sqrt{\frac{g H \Delta T}{T_i}} \quad 5\text{-}28$$

When the opening is large the air flow velocity varies a lot with the opening height, thus the air flow is integrated over its height which adds a 1/3 constant to the previous equation:

$$Q_{ij} = \frac{C_d A}{3} \sqrt{\frac{g H \Delta T}{T_i}} \quad 5\text{-}29$$

(Awbi, 2010)

This last equation will be used in the multi-room space model to determine the air flow between the rooms. It was previously represented by the variable Q_{ex} and will have a different value for each opening when an opening there is. It also means that new inputs will be added: the temperature inside of the rooms, and the size of the openings. Also it is important to note that in case there are two or more openings on the same wall, the flow through those openings is calculated using the equation 5-29 where A is the sum of the openings' areas, and H is the height difference between the lowest point of the lowest opening and the highest point of the highest opening.

5.3.3. Flow from an opened window

The second necessary parameter to include to the model is the air flow through opened windows. Indeed, it is an easy way to lower the mechanical air inflow rates when the outside temperature is high enough so that opening the windows would not cool down the building and therefore induce additional heating. The equation of the flow through an opened window is the same as the one from a general opening:

$$Q_w = C_d A \sqrt{\frac{2\Delta p}{\rho}} \qquad 5\text{-}30$$

Where:

- Q_w is the air flow through the window [m^3/s]
- C_d is the discharge coefficient
- A is the open area of the window [m^2]
- ρ is the density of air [kg/m^3]
- Δp is the pressure difference through the window [Pa]

About the discharge coefficient for a window, it needs to be evaluated in each case as it is an opening on the exterior. Thus an average constant value would induct to significant errors in the flow calculation.

(Heiselberg, 1999).

A window in a room does not usually stay open for a long period of time. The window is for example opened during a break between lessons or randomly by the occupants when they feel the need. Thus this parameter needs to be changed along the calculation period in the model. Besides, the air coming into the room from a window is outdoor air and its concentration of CO_2 is equal to the concentration of the inflow air coming in the room. Indeed the ventilation system sucks in the air from outside the building but near this building. The air coming into the room from the windows and the air coming from the air supply can thus be considered as identical. Therefore when an opened window will provide outdoor air flow to the room this airflow will be added to the mechanical air inflow in the calculation.

5.3.4. Multi-room space CO_2 model

Now that all the required parameters to build the multi-room space CO_2 model have been introduced, the multi-room space can be considered again. This is the same space as the one considered for the simplified multi-room model, i.e. three rooms and a corridor, each room having connections with its walls to at least one other room, the corridor, and outside with one or more windows. The Figure 5-4 shows these spaces with all the possible air flows: in blue are the outdoor air inflows for each room, in red are the air outflows for each room, and in green are the airflows from windows, with the subscript “w” and air flows from openings between neighboring rooms. In the Figure 5-4, the room 1 and 3 are not connected by any wall but in order to give some flexibility to this model there is a possibility to have an air flow between these two rooms, which nevertheless will never exist in my following examples. The other main parameters showed on the figure are the outside temperature, the temperature inside each room, the occupancy of the three classrooms, and the volumes of each room. Some other parameters used in the model are describing windows and openings between rooms.

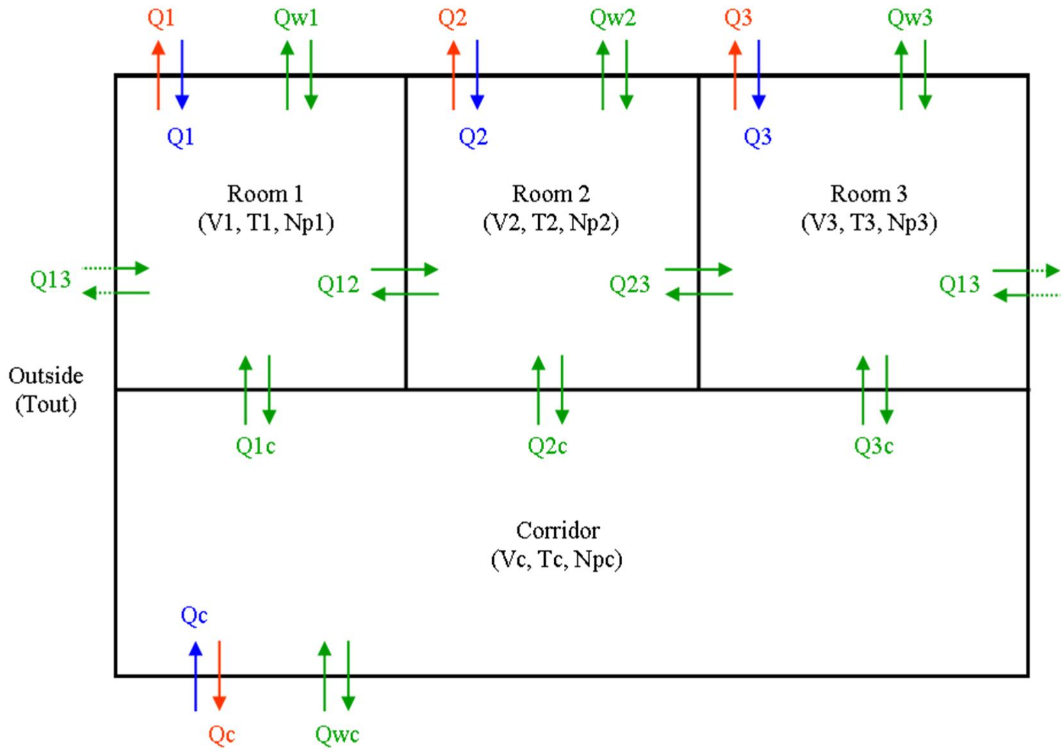

Figure 5-4 Description of the multi-room spaces and parameters

The differential equations of the CO_2 concentration in each room are obtained with the CO_2 balance of each room:

$$\begin{cases} \frac{dC_1}{dt}=\frac{G_1}{V_1}+n_1C_o+\frac{Q_{12}}{V_1}C_2(t)+\frac{Q_{13}}{V_1}C_3(t)+\frac{Q_{1c}}{V_1}C_c(t)-n_1C_1(t)-\frac{Q_{12}+Q_{13}+Q_{1c}}{V_1}C_1(t) \\ \frac{dC_2}{dt}=\frac{G_2}{V_2}+n_2C_o+\frac{Q_{12}}{V_2}C_1(t)+\frac{Q_{23}}{V_2}C_3(t)+\frac{Q_{2c}}{V_2}C_c(t)-n_2C_2(t)-\frac{Q_{12}+Q_{23}+Q_{2c}}{V_2}C_2(t) \\ \frac{dC_3}{dt}=\frac{G_3}{V_3}+n_3C_o+\frac{Q_{13}}{V_3}C_1(t)+\frac{Q_{23}}{V_3}C_2(t)+\frac{Q_{3c}}{V_3}C_c(t)-n_3C_3(t)-\frac{Q_{13}+Q_{23}+Q_{3c}}{V_3}C_3(t) \\ \frac{dC_c}{dt}=n_cC_o+\frac{Q_{1c}}{V_c}C_1(t)+\frac{Q_{2c}}{V_c}C_2(t)+\frac{Q_{3c}}{V_c}C_3(t)-n_cC_c(t)-\frac{Q_{1c}+Q_{2c}+Q_{3c}}{V_c}C_c(t) \end{cases} \quad 5\text{-}31$$

There are two ways to solve this system the first solution is analytical but it would be long and tedious to get the analytical equation by solving this system on paper. Nevertheless Matlab offers many solvers for ordinary differential equations, the one used here is “ode45”. It is a non-linear numerical method which implements a version of the Runge-Kutta 4th order algorithm. On Matlab it returns the numerical values of the equation system’s solution in a matrix form.

The second solution is numerical, from the finite difference method and is calculated step by step. The equations are similar as for the single room model obtained straight from the differential equation system. The system giving the CO_2 concentrations in each room is:

$$\begin{cases} C_1(i) = C_1(i-1) + \Delta t(C_{1_{in}} - C_{1_{out}}) \\ C_2(i) = C_2(i-1) + \Delta t(C_{2_{in}} - C_{2_{out}}) \\ C_3(i) = C_3(i-1) + \Delta t(C_{3_{in}} - C_{3_{out}}) \\ C_c(i) = C_c(i-1) + \Delta t(C_{c_{in}} - C_{c_{out}}) \end{cases} \quad 5\text{-}32$$

with the initial conditions:

$$\begin{cases} C_1(0) = C_{i1} \\ C_2(0) = C_{i2} \\ C_3(0) = C_{i3} \\ C_c(0) = C_{ic} \end{cases} \quad 5\text{-}33$$

The original equations for each room are relatively long and in order to keep the system readable and understandable two sub-variables are created for each equation of the system, e.g. $C_{1_{in}}$ and $C_{1_{out}}$ for the room 1. The first variable represents the amount of CO_2 contained by the air entering the room during the step and the second variable represents the amount of CO_2 leaving the room. For the room 1, the equations of these two variables are:

$$\begin{cases} C_{1_{in}} = \frac{G_1}{V_1} + n_1 C_0 + \frac{Q_{12}}{V_1} C_2(i-1) + \frac{Q_{13}}{V_1} C_3(i-1) + \frac{Q_{1c}}{V_1} C_c(i-1) \\ \qquad C_{1_{out}} = n_1 C_1(i-1) + \frac{Q_{12}+Q_{13}+Q_{1c}}{V_1} C_1(i-1) \end{cases} \quad 5\text{-}34$$

The equations are built the same way for rooms 2 and 3, for the corridor only the production of CO_2 due to occupants (e.g. $\frac{G_1}{V_1}$ for the room 1) is removed.

5.3.5. Comparison of the solutions

The comparison of the two solutions has been done with Matlab, the main script and the three functions' scripts are given in the appendix C. The multi-room space for this comparison has the same configuration as presented on the Figure 5-4 with three rooms (9 x 8 x 3 m) and a corridor (27 x 8 x 3 m, i.e. the volume of the corridor is equal to the volume of the three rooms together). The CO_2 concentration of the air supplied by the mechanical ventilation is 410 ppm. The other characteristics of each room are:

Room 1:

- 20 students
- Air supply: 150 dm^3/s
- Temperature: 295 K
- Initial CO_2 level: 410 ppm

Room 3:

- 30 students
- Air supply: 150 dm^3/s
- Temperature: 296 K
- Initial CO_2 level: 410 ppm

Room 2:

- 5 students
- Air supply: 150 dm^3/s
- Temperature: 294 K
- Initial CO_2 level: 410 ppm

Corridor:

- Air supply: 75.6 dm^3/s (i.e. 0.35 $dm^3/(s\ m^2)$, cf. part 3.1.2)
- Temperature: 294 K
- Initial CO_2 level: 410 ppm

Between the rooms 1 and 2 there is an opening of 1 x 2 m, and the door between the room 3 and the corridor is open, its size is 0.8 x 2 m. The airflows through these openings are therefore calculated with the equation 5-29, for the airflow between rooms 1 and 2 it gives:

$$Q_{12} = \frac{C_d A}{3}\sqrt{\frac{gH\Delta T}{T_i}} \qquad 5\text{-}35$$

with:

$$\begin{cases} H = 2\,m \\ A = 1 * 2 = 2\,m^2 \\ g = 9.81\,m/s^2 \end{cases} \quad and \quad \begin{cases} \Delta T = T_1 - T_2 = 1\,K \\ T_i = \frac{T_1 - T_2}{2} = 294.5\,K \\ C_d = 1 \end{cases} \qquad 5\text{-}36$$

Thus replacing the values of 5-36 into 5-35 gives $Q_{12} = 172\,dm^3/s$, whereas with the same equation and the corresponding data, the airflow through the door of the room 3 is $Q_{3c} = 195\,dm^3/s$. The time constants for the three rooms are the same:

$$\tau = \frac{1}{n} = \frac{V}{Q} = \frac{216000}{150} = 1440\,s = 24\,min \qquad 5\text{-}37$$

For the calculation the time step chosen is 2 min (inferior to $\tau/10$) and the length of the calculation period is 120 min (equals to 5τ). The Figure 5-5 gives the results of the calculation of the CO_2 concentrations in each room with the two solutions. The maximum relative error taking as a reference the approximation from “ode45” Matlab solver of the analytical solution is displayed for each room on each graph. All the error values are very small (inferior to 2 %) and it is therefore possible to conclude that the two solutions are equivalent and give the same results, with an appropriate time step.

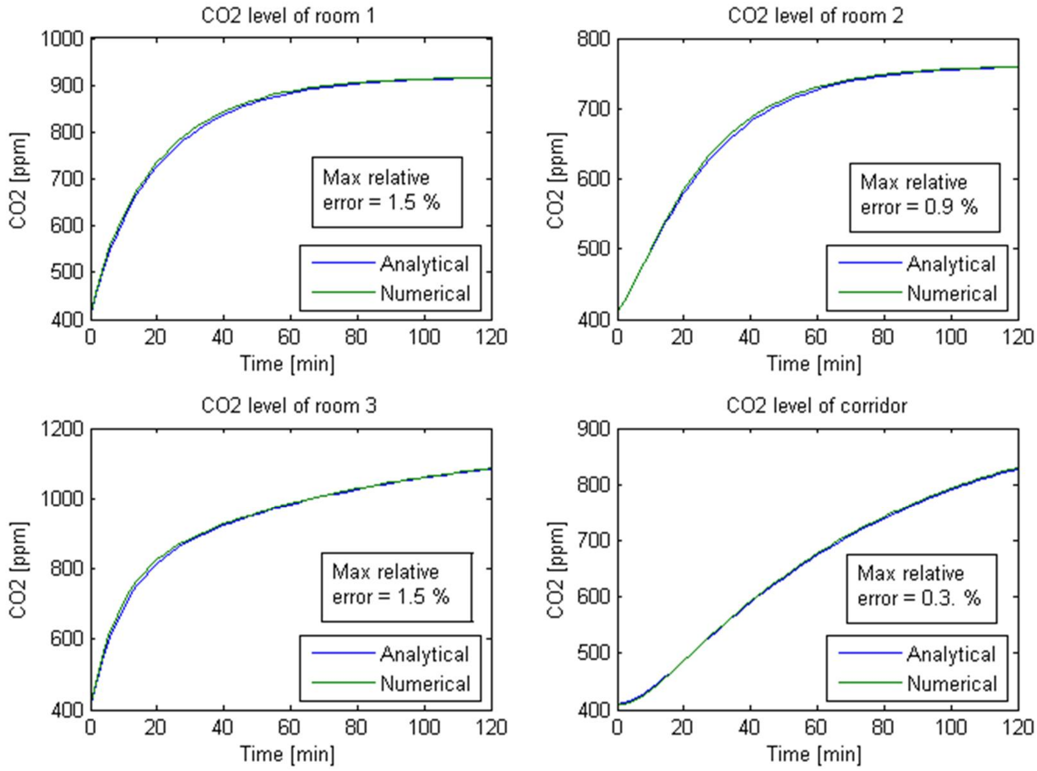

Figure 5-5 Comparison of numerical and approximated analytical solutions for the multi-room CO_2 model

The numerical solution from finite difference method allows changing most of the values for each time step such as occupancy, flow rates through neighboring rooms' openings or through windows. Moreover the time step required will stay in the order of magnitude of 1 min which does not generate long calculation time. This numerical solution from the finite differences method is easy to implement that is the reason why this solution is preferred for the rest of this study. The multi-room CO_2 concentration model has been implemented on Excel and Visual Basic, this calculation interface is presented in the appendix D and it has been used for the comparisons between measurements and the predictive CO_2 model.

6. Experimental measurements

6.1. Description of the building

The department of Mechanics and Design is situated in the building Konetalo (or "Machine building" translated to English) and the measurements are also conducted in this building. The department and the different rooms where measurements take place are situated in the first floor of the building. Two drawings of this floor of the buildings with and without the ventilation circuits are presented in the appendix E.

6.1.1. Rooms

The two first rooms K1303 and K1308 are used only for lectures and are not open to students outside of these teaching sessions. They have two different ventilation configurations, the first one K1303 has the supply vents on one side and exhaust vents on the other side of the room, for K1308 supply and exhaust vents are on the same wall. Thus these differences can lead to difference in the air mixing and the ventilation efficiency of the room. The dimensions of the rooms are:

Room K1303:

- Height: 3.10 m
- Width: 5.65 m
- Depth: 8.13 m

Room K1308:

- Height: 3.05 m
- Width: 5.95 m
- Depth: 7.05 m

The two other rooms K1242 and K1243 are equipped with computers with CAD and FEM software, LabView etc. Outside of teaching sessions they are open to all students twenty-four hours a day and seven days a week. The Figure 6-1 is a picture of the inside of the room K1243 and shows the different sensors on the central pole. The dimensions of the rooms are:

Room K1242:

- Height: 3.01 m
- Width: 9.19 m
- Depth: 8.11 m

Room K1243:

- Height: 3.01 m
- Width: 8.84 m
- Depth: 8.11 m

Figure 6-1 Computer room K1243

6.1.2. Ventilation

In the building the mechanical ventilation is centralized and there are two separate networks covering each half of the first floor for air supply and air removal. From Monday to Tuesday the mechanical ventilation is on from 6.00 am to 5.00 pm and from 6.00 am to 4.00 pm on Friday. The air supply is off during nights and weekends and a small extraction is maintained. In the rooms there are different types of vents for the air supply and the air extraction, and the ventilation configuration is thus not always the same. The vents installed in the rooms concerned by measurements are presented here.

For the air extraction, the vent's models KSO-160 (illustrated on the Figure 6-2) and KSO-200 from the company Fläktwoods are installed in the different rooms of Konetalo's first floor. The amount of air extracted is adjustable and can be determined using the technical documentation given in the Figure 7-13 in the appendix F. The formula giving the airflow through the vent is:

$$Q = k\sqrt{\Delta p_m} \tag{6-1}$$

where:

- Q is the airflow through the vent [dm^3/s]
- k is a coefficient, its value depends on adjustment
- Δp_m is the measured pressure difference through the vent [Pa]

The pressure difference measurement and determination of the coefficient k are described in the Figure 7-12 in the appendix F. (Fläktwoods Oy, 2007).

Figure 6-2 Fläktwoods' exhaust vent KSO-160 in room K1243

Except in the room K1308, for the inlet vents, the vent's model is the CYLP-16 from the company Fläktwoods, illustrated on the left part of Figure 6-3. The airflow rate is adjustable from inside the vent and the equation 6-1 can be used to calculate this flow rate. The measurement of the pressure difference is explained in the Figure 7-11 in the appendix F, for the model CYLP-16 the inside diameter is 160 mm and the corresponding k coefficient is equal to 25.3 (version DTTZ).

Figure 6-3 Fläktwoods CYLP-16 (left) and RCL Climecon OKE-160 (right)

In the room K1308, the inlet vent is the model OKE-160 from the company RCL Climecon, showed on the right side of Figure 6-3. The equation 6-1 can also be used to determine the airflow rate and the measurement of the pressure difference and determination of the coefficient k is explained in the Figure 7-14 the appendix F.

In the appendix G are presented all the measurement systems that had been used during all the experiments. The WIREPAS sensors system is describe in the part G-1, and the other hand devices in the part G-2.

6.2. Correlation between model and measurements

6.2.1. CO_2 concentration in a room with variable occupancy

This experiment took place in the room K1243 where four CO_2 sensors were positioned on a pole in the middle of the room, one at 10 cm above the floor, one at 1.1 m corresponding to the breathing zone when sitting, one at 1.8m corresponding to the breathing zone when standing and the last one at the ceiling. The idea was to check if there was a concentration variation according to height for CO_2. This experience lasted over a day on 22.02.12 from 10 am to 5 pm. Indeed, it is a room in free access 24/7 a long period was thus needed to get an overview of the occupancy changes. The students were counted in the room every ten minutes and entered in an excel worksheet in order to know the real occupancy of the room. The outview of the occupancy over the day is given on the Figure 6-4. This figure shows quite clearly that the number of student in the room except during the lecture time between 10:15 and 11:45 was changing a lot and sometimes quickly, around 14:00 for example.

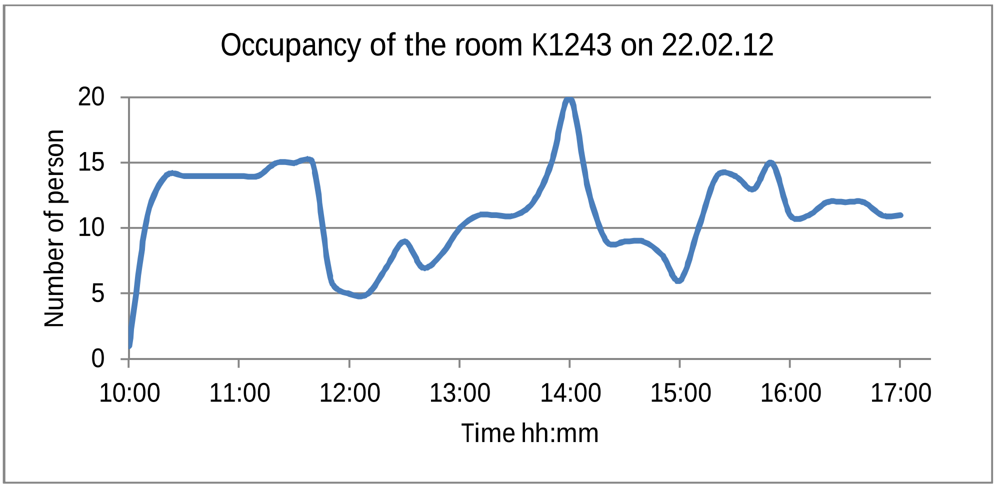

Figure 6-4 Outview of the occupancy over the day

All the characteristics of the room (dimensions, supply flow rate = 193 dm^3/s, beginning CO_2 concentration = 410 ppm) and the occupancy have been used as input in the single room model to calculate the theoretical CO_2 concentration level in the room along the day. Then the measurement values from the WIREPAS have been collected and both experimental and theoretical values are showed on the same graph on Figure 6-5 in order to make comparison.

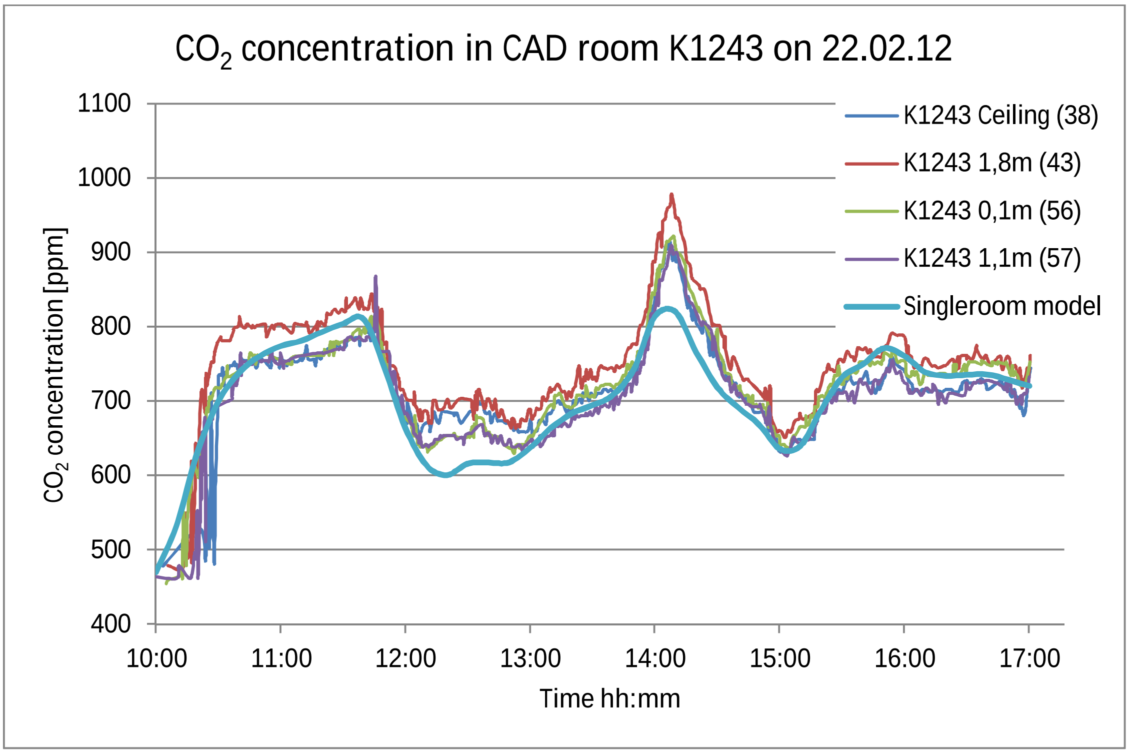

Figure 6-5 Comparison between Single room model and measurements

The conclusion from this comparison is first that the overall shape of the calculated concentrations fits with the measurements values which confirm the model's validity for an isolated room with variable occupancy. Secondly the graph shows differences between theory and measurements around 12 pm and 2 pm. At 2 pm there is a peak in the CO_2 concentration which is also seen in the occupancy graph but on the model curve it is softer because of the 10 min step for occupancy change. After 12 pm, students were leaving the lecture and new students were entering the room and during this period counting every 10 minutes was not totally accurate which could explain the difference in concentrations. In the room the average occupancy between 12:00 and 13:00 was slightly higher than the measured one. But finally this experience shows that by knowing the average occupancy of this room, supply flow rate can be adjusted to fit with the allowed limit by using the predictive model. Here it could be lowered because the maximum CO_2 concentration measurement is about 900 ppm.

Another comment is that all the four sensors give similar values if we consider the resolution of those one which is about 50 ppm. It is thus not showing any difference in CO_2 concentration regarding the height of their position in the room.

6.2.2. Effect of an opening between neighboring rooms

For the need of the project a hole has been made in the wall between the two computer rooms of the size of a door, 2.47 m high and 1.16 m wide. The opening was kept closed by insulating material which could be easily removed. On the day of the experience, 27.03.12, the mechanical air flow rate in the room K1243 was reduced to

120 dm^3/s (one air inlet had been closed as well as two outlets to keep the balance between the air inflow and outflow) and students were counted every ten minutes from 13:20 to 16:30. The Figure 6-6 shows the evolution of the occupancy of the two rooms between 13:30 and 16:30. Before 14:50 the room K1242 was closed to students and was thus empty. After 14:50 the graph shows that the occupancy of the room K1243 decreases when it increases in the other room, and the two rooms have almost the same occupancy after 16:00.

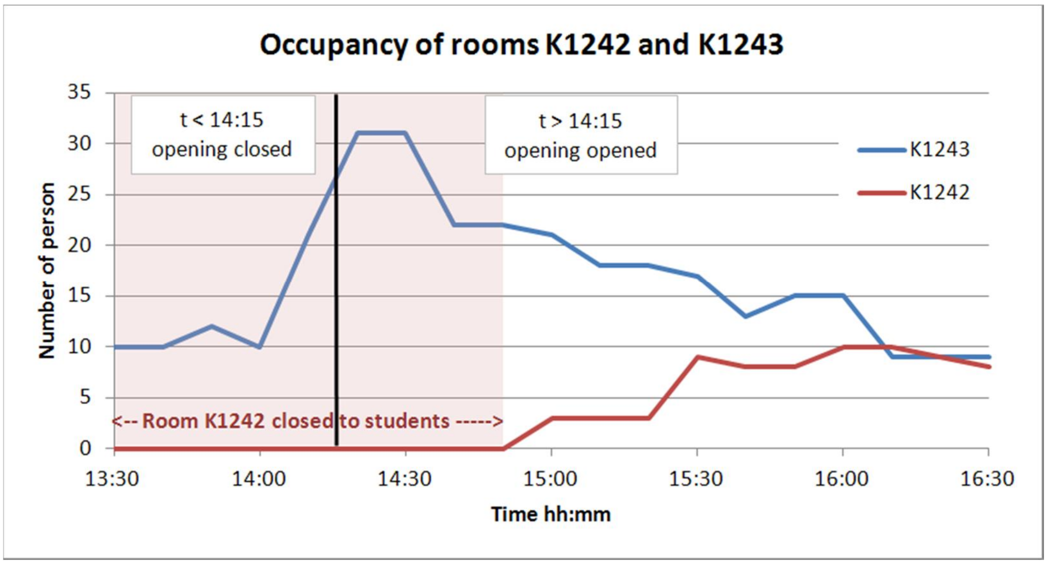

Figure 6-6 Occupancy of the rooms K1242 and K1243 on 27.03.12

At 14:15, when the room K1243 was occupied by 31 students and the other room was totally empty with a low CO_2 concentration (about 470 ppm), the hole in the wall between the rooms was opened. The airflow through this opening was calculated from the equation 5-29 and equals to 149 dm^3/s. The temperature difference calculated with the average temperatures in both rooms over the period (14:15 to 16:30), T_{K1242} = 24.3 ºC and T_{K1243} = 24.0 ºC, thus ΔT = 0.3 K and T_i = 297 K.

The Figure 6-7 and the Figure 6-8 are showing the measured concentrations of CO_2 compared with the calculated CO_2 concentrations from the models, respectively in room K1242 (empty) and K1243. The opening is only taken into account by the multi-room CO_2 model thus the difference between the two calculation models will show the effect of the opening on the CO_2 concentration of the room. The initial CO_2 concentrations at 13:20 were 1265 ppm in room K1243 and 470 ppm in room K1242.

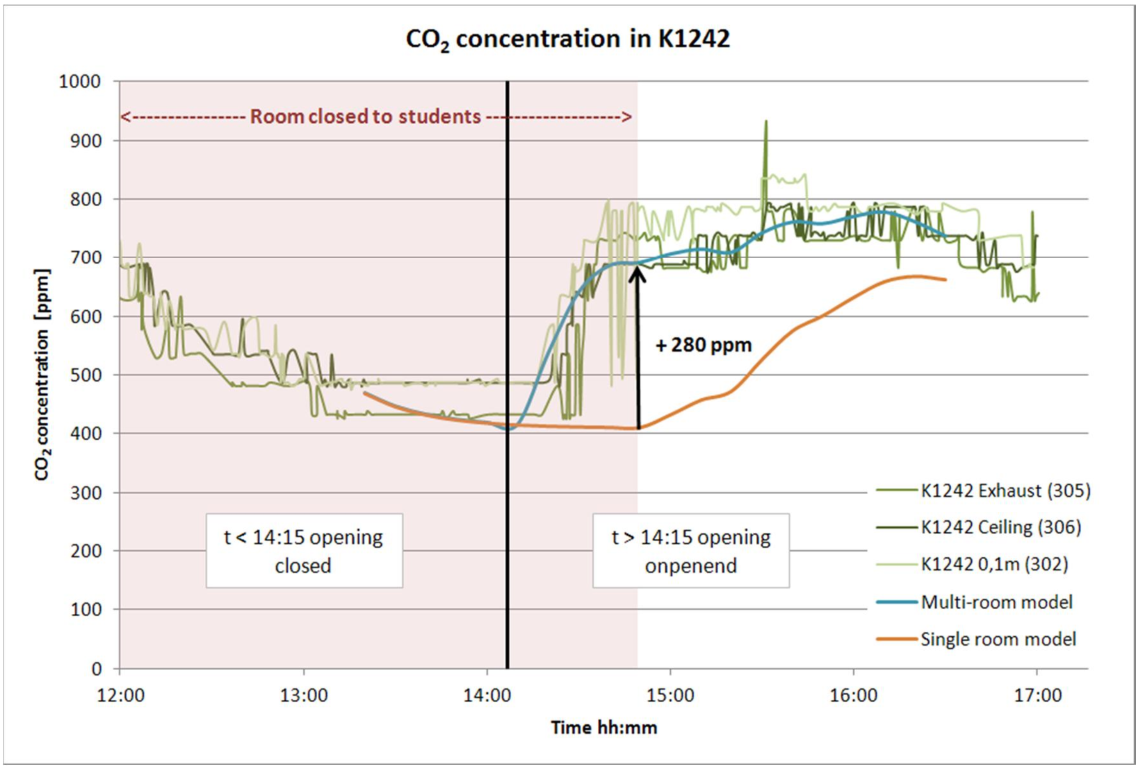

Figure 6-7 Effect of the opening on the CO_2 concentration in room K1242

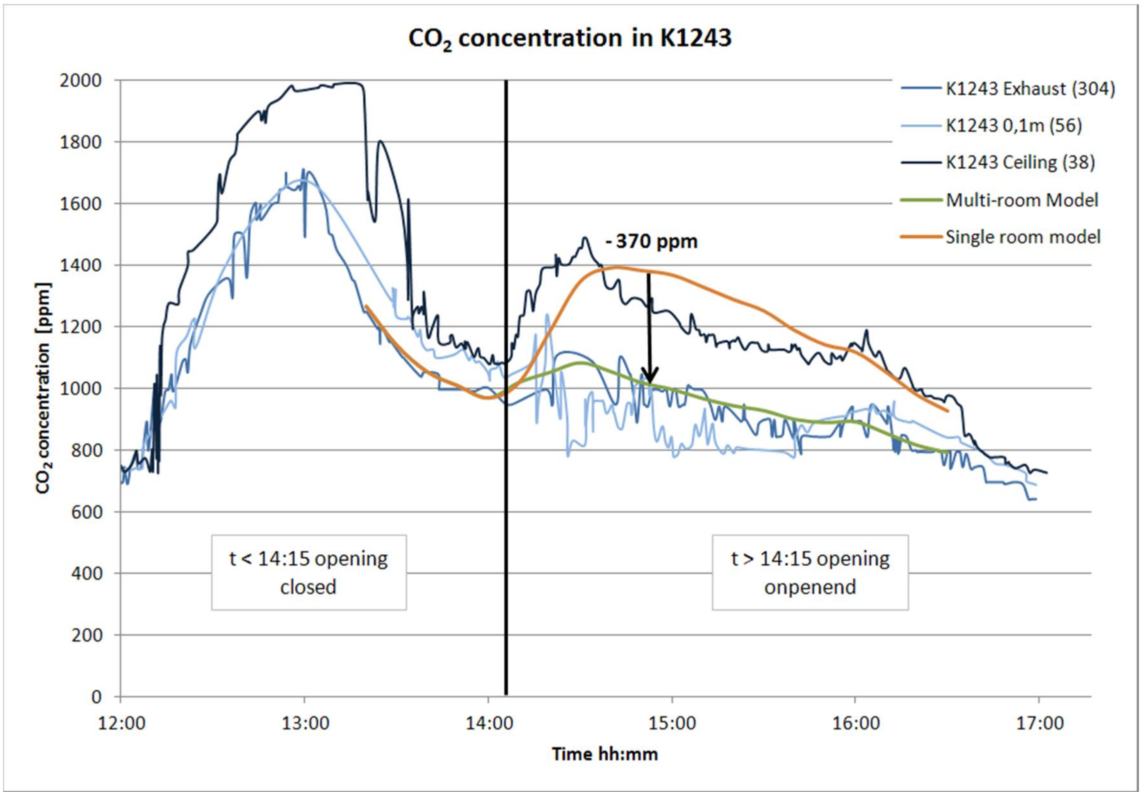

Figure 6-8 Effect of the opening on the CO_2 concentration in room K1243

Between 14:15 and 14:50 the increase in the CO_2 concentration in the room K1242 is only due to the opening and the maximum difference between values from single room and multi-room models is +280 ppm, which was reached just before the first students entered that room at 14:50. In the room K1243 the comparison between the two models gives a difference of -370 ppm with the opening at 14:50. After 14:50 students entered the room K1242 and the occupancy of the room K1243 decreased. The effect of the opening was thus decreasing due to both to the fact that the CO_2 concentrations tend to be even in the two rooms after some time and that the occupancy of the two rooms are similar at the end of the experiment. It can be seen on Figure 6-7 and Figure 6-8 that after 16:00 the difference between the single room and multi-room CO_2 models is much smaller, from 100 to 150 ppm.

The first comment about these results is the good correlation between the measured values in each room and the calculated values from the multi room model. Also in the Figure 6-8 the sensor on the ceiling (38) is showing much higher values than the others in the room during and after the period of high occupancy. One reason for this could be its position, on a concrete beam on the ceiling which is hardly reached by the light air buoyancy in the room. Nevertheless this experiment confirms the validity of the multi-room model with an opening between neighboring rooms.

The second comment is the effect of the opening between two neighboring rooms. This experiment shows that the CO_2 concentration in the occupied room has been reduced by almost 400 ppm, i.e. the maximum value was about 1000 ppm instead of 1400 ppm without the opening. It means that the CO_2 concentration has been reduced by 30 % without any increase of the mechanical ventilation rate of the room.

6.2.3. CO_2 concentration drop in a room: room closed, windows opened, and neighboring rooms' openings

The goal of this experiment was to compare the effect of opening the windows and different configuration of neighboring rooms' openings on the CO_2 concentration drop in a room. This test took place in the two CAD rooms K1242 and K1243 where there was the possibility to use the large opening between the two rooms in different configurations. The experience was made during the day with the normal mechanical ventilation rates which were measured before the test (some adjustments were made in these rooms): for the room K1242 +176 dm^3/s and -202 dm^3/s, and for the room K1243 +185 dm^3/s and -205 dm^3/s. In each room there were three CO_2 sensors, one near an exhaust vent, and two in the middle of the room at 1.1 m and 1.8 m from the floor. The temperatures were measured in the rooms at the exhaust and outside the building.

Four different tests have been made under the same initial conditions but in different configurations. The CO_2 concentration in the room K1243 was raised above 3000 ppm with the help of a bottle of CO_2 gas, then the bottle was closed and the decrease of the CO_2 concentration was measured. The five different configurations are:

- The room closed
- The room with an opening near the ceiling (1.11 x 1.16 m)

- The room with two openings: one near the floor (0.49 x 1.16 m) and one near the ceiling (0.64 x 1.16 m)
- The room with three windows opened

During each test the starting time was determined when the values from the sensors started to decrease. The decrease starting point was coming a few minutes after the bottle had been closed. Indeed, it corresponds to the time the CO_2 gas needs to spread evenly in the room. Having the same starting concentration was not an easy thing to achieve because the outlet control of the bottle was limited to a pressure valve without a flow indicator. Nevertheless all the CO_2 concentration starting points are included between 3000 and 3350 ppm. The time constants of the CO_2 concentrations' drop curves and the time needed to have the CO_2 concentration at 5 % of the starting value are used here to compare the different situations between each other. The CO_2 concentration's decrease in the closed room was giving the reference values for the comparison. The use of gaps between the room and its neighboring room, and the addition of natural ventilation from windows, are to be compared with the reference and between them. The aim of using two different configurations for the opening between the two rooms was to compare their effects on speed of decrease.

The Figure 6-9 gives the measured CO_2 concentrations from the three sensors of the room K1243 and the calculated CO_2 concentration from the single room model during an hour after the starting point. The equations of the curves are in the format ae^{-bt}, where a is the value at t=0 and 1/b is the time constant. An average of the three time constants from the three sensors thus gives the average measured time constant.

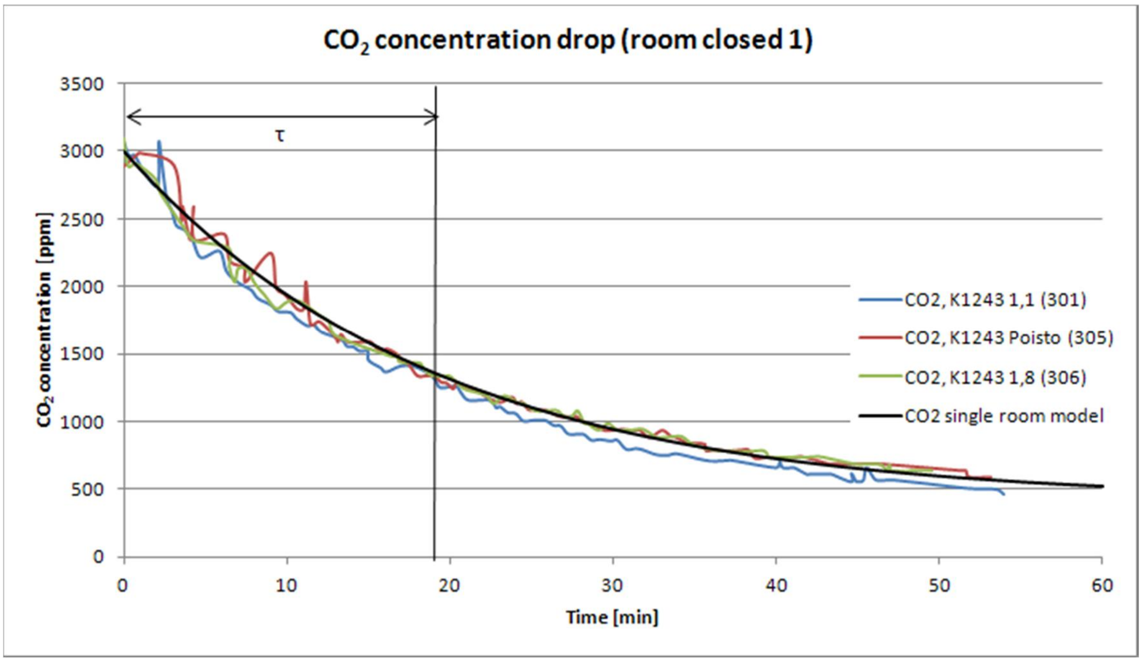

Figure 6-9 Drop of the CO_2 concentration in the closed room

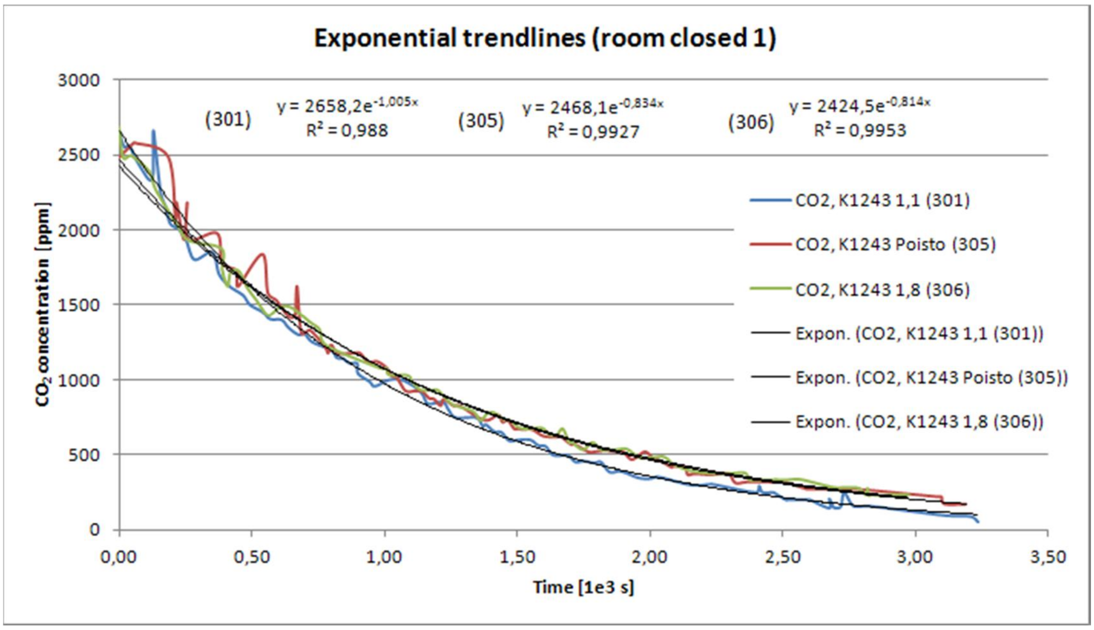

Figure 6-10 Exponential trend lines for each sensors, room closed

In the Figure 6-10 the CO_2 concentration of the outside air (measured at 410 ppm) has been removed from the concentration values of the sensors. The exponential trend line of the Excel gives an estimate equation of the sensors' values and the time constant for each sensor is given in these equations. The average measured time constant is τ_m = 18.01 min = 19 min 01 s and the measured time in order to reach 5 % of the initial value is $t_{5\%}$ = 55 min 52 s. The mechanical flow rate in the room can be calculated from the measurements since $\frac{1}{\tau} = \frac{Q}{V}$. From the CO_2 concentration measurements it gives here Q = 191 dm³/s. The measured mechanical flow rate was 185 dm³/s, the relative difference is therefore about 3.25 %. The time constant of the model is calculated from the mechanical flow rates and is thus equal to 19 min 26 s and $t_{5\%}$ = 58 min 13 s.

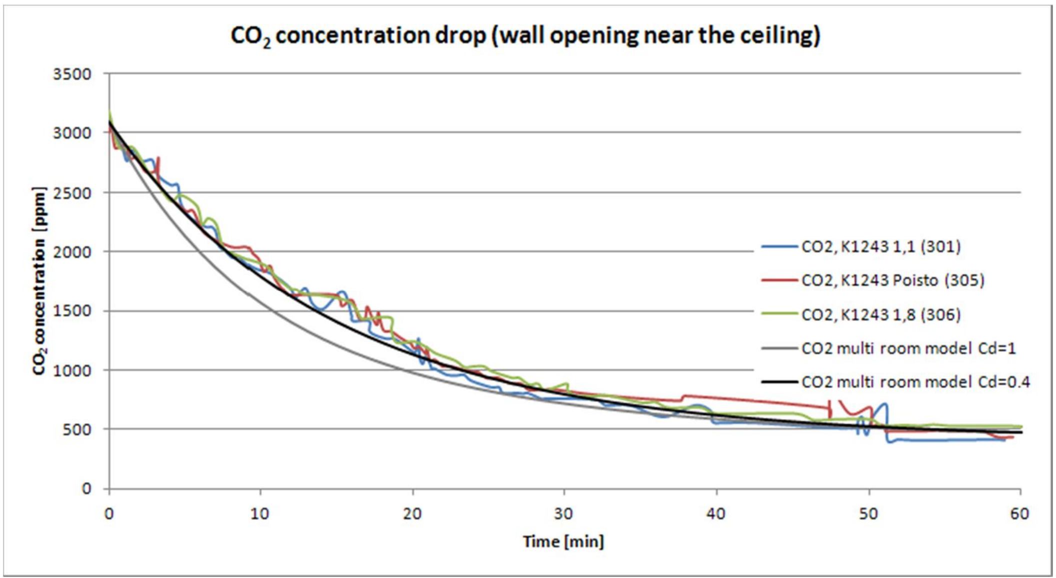

Figure 6-11 Drop of the CO_2 concentration in the room with an opening in the wall near the ceiling

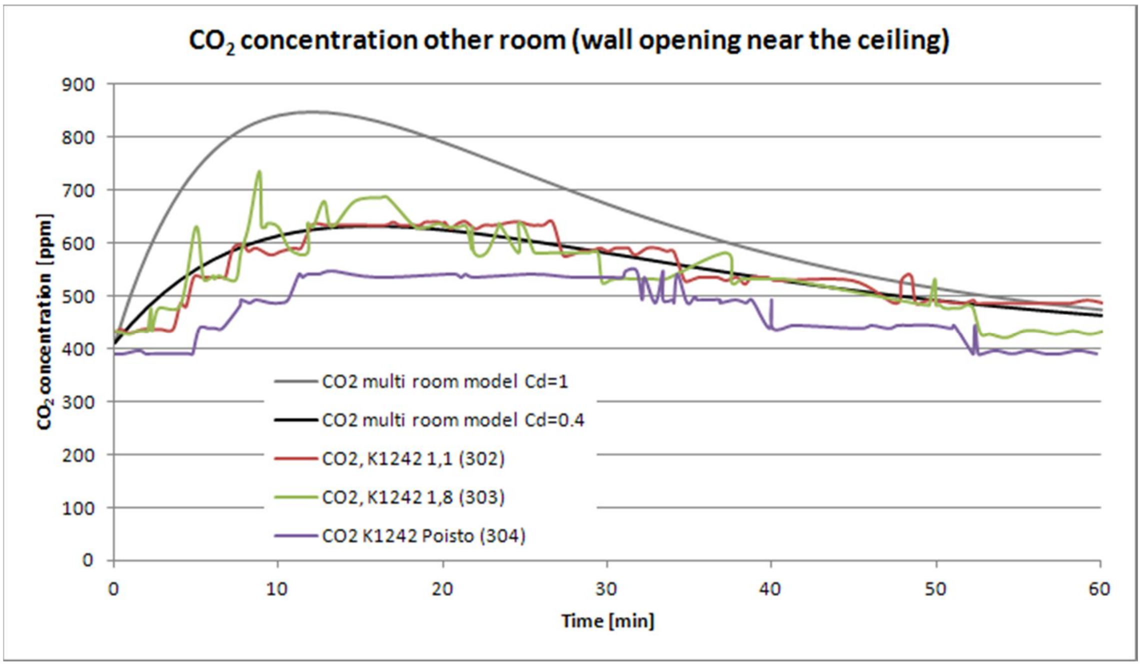

Figure 6-12 CO_2 concentration in the neighboring room due to the wall opening near the ceiling

The Figure 6-11 shows the decrease of the CO_2 concentration in the room with the gap near the ceiling. For the measurement values the same analyze had been made as for the first test to determine the characteristics of the curves with the exponential trend lines. The measured time constant is $\tau_m = 15\,\mathrm{min}\,48\,s$ and the time to reach 5 % of the initial value for the measurements is $t_{5\%}$ = 46 min 28 s. The temperature in the room K1243 was 23.5 °C and 21.1 °C in the room K1242, thus with a temperature difference of 2.4 K, the corresponding theoretical air flow is $Q_{op1} = 127.7\,\mathrm{dm^3/s}$ with a discharge coefficient C_d = 1. The CO_2 concentrations calculated with the multi-room model in the two rooms are represented in the Figure 6-11 and the Figure 6-12 by the light grey curves. It is clear that the CO_2 concentration is decreasing faster in room K1243 and reaches too high values in the second room. The discharge coefficient cannot be calculated but only estimated, a wrong assumption can thus be the reason of the difference. Different values of this coefficient have been tried and when C_d = 0.4 the calculated CO_2 concentrations are very close to the measured values in both rooms , see the black curve in the Figure 6-11 and the Figure 6-12. The flow rate through the gap with C_d = 0.4 is now $Q_{op0.4} = 51.1\,\mathrm{dm^3/s}$ and the corresponding time constant is 15 min 36 s and $t_{5\%}$ = 49 min 13 s. It was 10 min 47 s and 45 min 45 s for the time constant and $t_{5\%}$ respectively with C_d = 1. The smaller value for the discharge coefficient shows the importance of the total height of an opening compared to the height of the room for the efficiency of such gap between rooms.

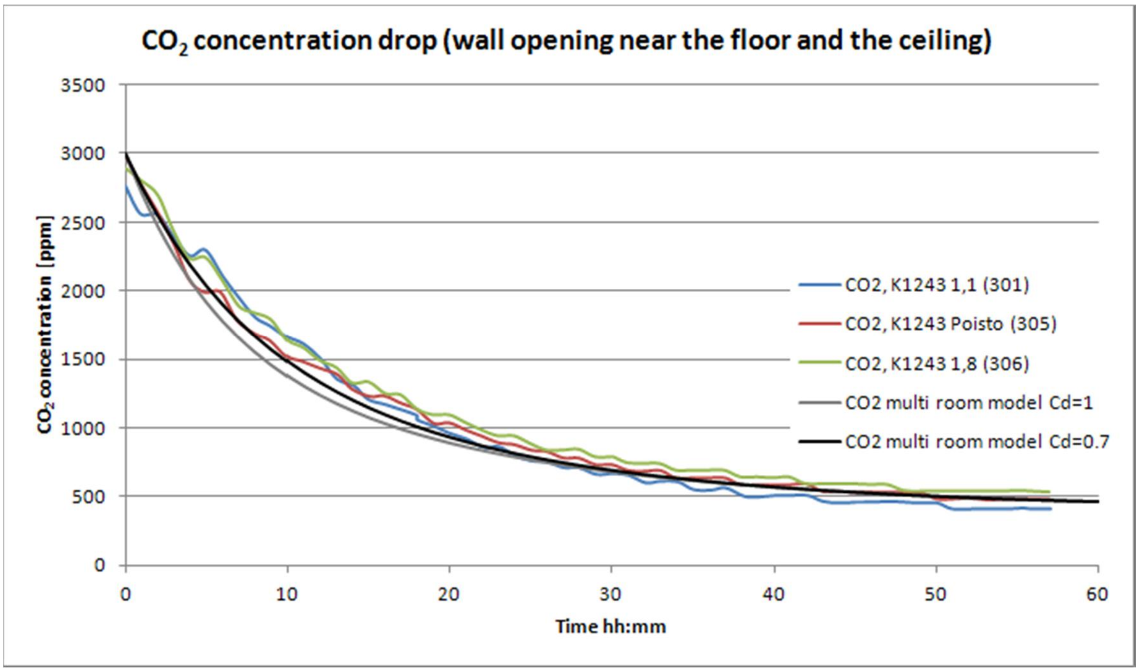

Figure 6-13 Drop of the CO_2 concentration in the room with two openings in the wall, one near the floor and one near the ceiling

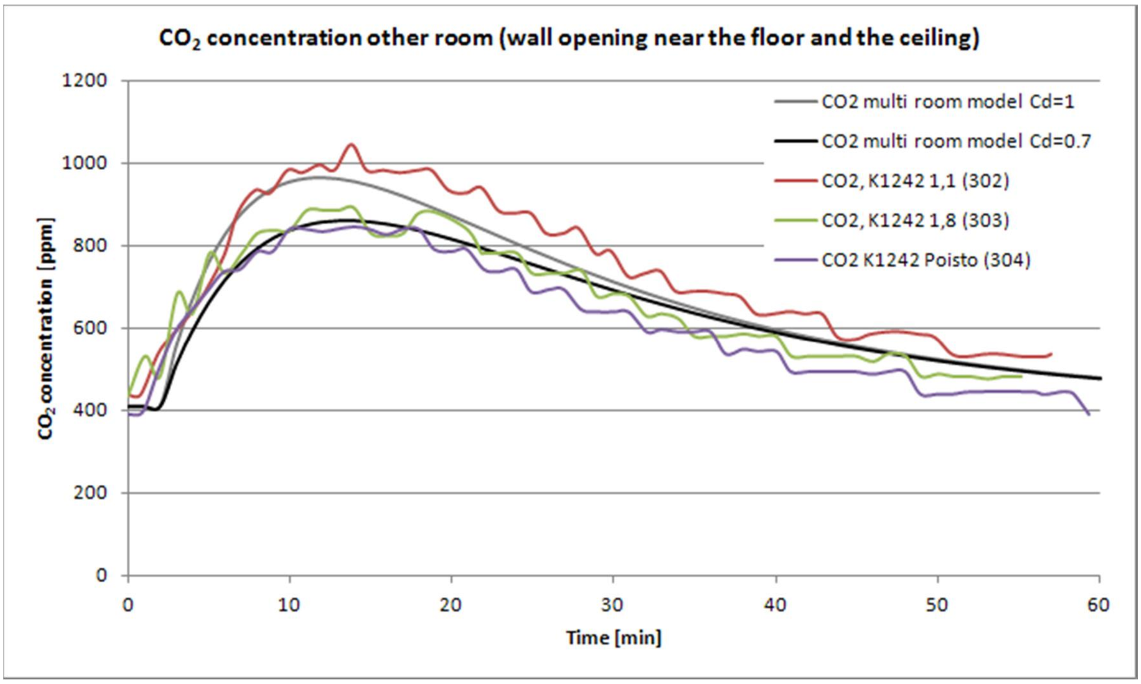

Figure 6-14 CO_2 concentration in the neighboring room with the split wall opening, one part near the floor and the other part near the ceiling

For the third test, the opening between the two rooms is split in two parts, one near the floor and one near the ceiling, and the total area is less than 2 % bigger than for the previous test. The temperature in the room K1243 was 23.5 ºC and 20.9 ºC in the room K1242, thus with a temperature difference of 2.8 K, the corresponding theoretical air flow is $Q_{op1} = 209.4\,dm^3/s$ with the discharge coefficient $C_d = 1$. It is important to note that in this case, the two openings were placed at different heights on the wall, thus the height H used to calculate Q_{op1} with the equation 5-29 is the distance from the lowest point of the floor opening to the highest point of the ceiling opening, here it is 2.47 m. And the area A is the sum of the areas of the two openings. The Figure 6-13 and the Figure 6-14 are respectively showing the CO_2 concentration decrease in the rooms K1243 and K1242. They compare the values from the sensors with the calculated values from the multi-room CO_2 model. With the Excel exponential trend lines the characteristic values are calculated for measurements, are $\tau_m = 14\,\text{min}\,06\,s$ and $t_{5\%}$ = 40 min 31 s, for the CO_2 model with C_d = 1 $\tau_{th1} = 10\,\text{min}\,47\,s$ and $t_{5\%}$ = 45 min 44 s. The difference between the time constants is important (about 23 %). Lower values of the discharge coefficient have been tried and with C_d = 0.7 the flow rate through the gap is $Q_{op0.7} = 167.5\,\text{dm}^3/\text{s}$, the time constant $\tau_{th0.7} = 12\,\text{min}\,05\,s$ and $t_{5\%}$ = 45 min 52 s. The Figure 6-14 shows that the second curves from the CO_2 multi-room model with Cd = 0.7 is close to the minimum values received from the sensors, and with C_d = 1 it is closer to the maximum measured values. The value of this discharge coefficient for this split opening between the rooms is included in the interval [0.7 1]. Although the Figure 6-13 and the Figure 6-15 which show a comparison between the CO_2 multi-room model with the two values of C_d and the concentrations for the average of the sensors values indicate better results with the lowest value C_d. This third test shows first that this opening in two parts is more efficient than the same area opened in one part and also that having a good estimation of the value of the discharge coefficient is not easy.

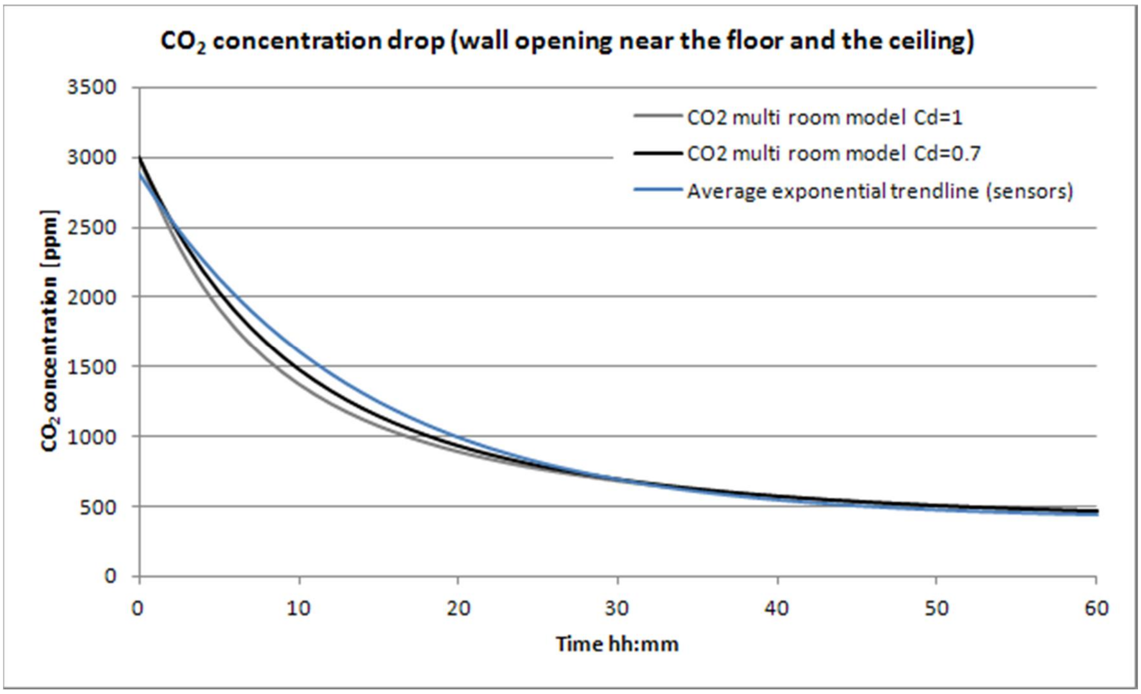

Figure 6-15 CO_2 concentration from predictive model and average of exponential trend lines from sensors, wall openings floor and ceiling

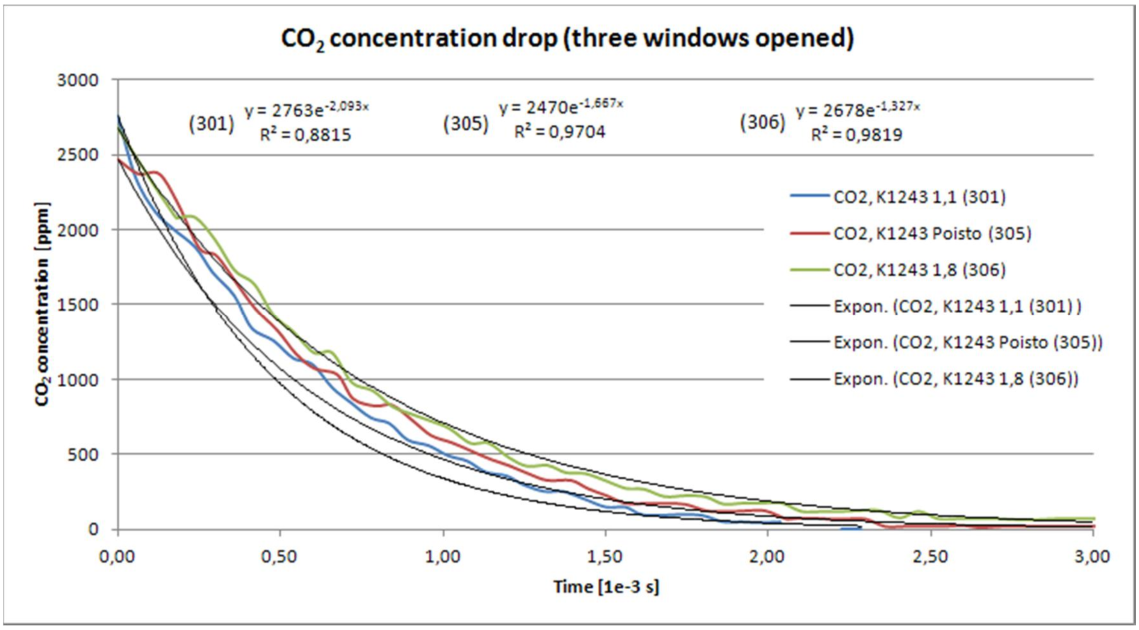

Figure 6-16 Drop of the CO_2 concentration in the room with three windows opened

During the last test three windows were opened, the pressure difference for each of window was measured, ΔP = 0.8 Pa. The effective opening of each window was 1.38 x 0.08 m and the discharge coefficient was not known. The Figure 6-16 shows the measured CO_2 concentration in the room (minus 410 ppm from outside air) and the Excel exponential trend lines of each sensor curves. The average time constant is $\tau_m = 9\,\mathrm{min}\,50\,s$, which corresponds to a mechanical ventilation rate of $\mathrm{Q} = 366\,\mathrm{dm^3/s}$. Moreover the measured mechanical ventilation rate is $\mathrm{Q_m} = 185\,\mathrm{dm^3/s}$, thus the rate due to the opened windows is $\mathrm{Q_w} = 181\,\mathrm{dm^3/s}$ equivalent to 60.3 $\mathrm{dm^3/s}$ per window. The discharge coefficient can then be calculated with this value and the windows' characteristics in equation 5-30, thus $C_d = \frac{Q}{A\sqrt{\frac{2\Delta P}{\rho}}} = 0.47$. The calculated CO_2 concentration are compared to the sensor values on the Figure 6-17 where is also presented for comparison the evolution of the CO_2 concentration in the room closed.

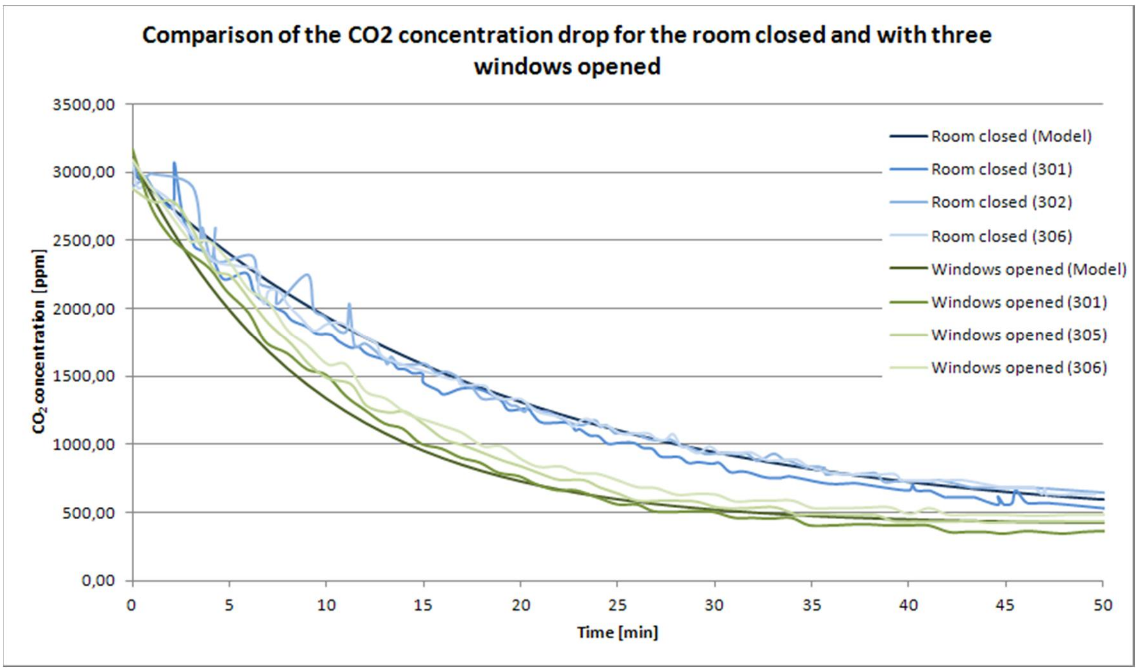

Figure 6-17 CO_2 concentration drop from 3000 ppm for the room closed and for the room with three windows opened

The Figure 6-17 shows the two extreme cases for the CO_2 concentration decrease in the room K1243, the slowest when the room is closed, and the fastest when three windows are opened. The speed of the decrease is two times faster with the three windows opened than with the room closed. It represents a difference of half an hour between the two situations in order to get CO_2 concentration in the room under 5 % of initial concentration C_0*[6]. The Table 3-1 summarizes the comparison between the four tests; it compares the time constants and the time needed for the CO_2 concentration to decrease to 5 % of the starting concentration from the calculation model and the measurements for each situation.

Table 6-1 Characteristics values for the four tests

	Model		Measurements	
	τ (at 0.368 C_0*)	$t_{5\%}$ (at 0.05C_0*)	τ (at 0.368 C_0*)	$t_{5\%}$ (at 0.05C_0*)
Room closed	19 min 26 s	58 min 13 s	19 min 01 s	55 min 52 s
Wall opening near the ceiling	15 min 36 s	49 min 13 s	15 min 48 s	46 min 28 s
Wall opening near the floor and the ceiling	10 min 47 s	45 min 44 s	13 min 53 s	40 min 50 s
Three windows opened	9 min 51 s	29 min 31 s	10 min 04 s	29 min 12 s

[6] C_0* is the initial CO_2 concentration above the concentration of the outside air, 410 ppm

First this experiment proves that using windows or neighboring rooms can significantly increase the speed of the CO_2 concentration decrease in a room. A CO_2 concentration level close to the outside concentration can thus be achieved within half an hour under good conditions. Especially windows are very efficient when the weather is sufficiently warm. Indeed if the outside air is too cold it will cool down the room and induce additional heating in order to maintain the normal room temperature.

Second comment is the comparison between the two different openings on the wall between the two rooms. For the same area opened, dividing the opening in two parts, one near the floor and one near the ceiling is twice more efficient due to the discharge coefficient and the total height. It seems that for an opening of a relative small height compared to the total height of the room, the discharge coefficient cannot be assumed to be equal to 1 but when this difference gets smaller C_d increases. Nevertheless estimating the value of the discharge coefficient is a critical point in order to model the flow through neighboring rooms' openings and only further analyze and experiment could give more reference values for different configurations.

Nevertheless this experiment is showing that the predictive multi-room model for the CO_2 concentration is flexible and is very close to the measured values in all the different case when the input parameters are carefully evaluated. This also shows that using ventilation between the rooms of a space can provide good alternative to higher mechanical ventilation rates.

7. Application and conclusion

7.1. Control of ventilation flow rates

The mathematical predictive model for the CO_2 concentration in multi-room spaces which has been described in this work can be used to build a new predictive control model for ventilation systems. The objective of this control model is to use the different possibilities offered by the windows and the neighboring rooms to maintain the CO_2 concentration under the defined limit before increasing the mechanical ventilation rates.

In the information required initially to establish the limit conditions for the use of windows and the openings between rooms. These limits are represented by the number of windows in each rooms and their sizes, the number of possible openings between neighboring rooms (this includes doors) and their sizes, and finally the maximum mechanical ventilation rate in each room. The initial situation for the space is given by:

- Reduced mechanical ventilation rate to 40 % of the maximum value
- All the windows closed
- All the openings between the rooms closed

From this initial situation the predictive calculation model is used to calculate the CO_2 concentration for the next time period which is also defining the time step of the control model. Then the maximum CO_2 concentration in each room is compared to the limit concentration, in a room, if the maximum is over the limit, then the different options are treated in the following order:

- If the outside temperature is superior to the defined minimum temperature to allow windows' opening (to avoid extra heating in the room) then one more window is opened.
- If opening the windows is not possible and if there is a neighboring room with a maximum CO_2 concentration lower than the limit then an opening between these rooms is opened. In case there are many of these neighboring spaces with better air conditions, the classroom with the lowest maximum CO_2 concentration is chosen first, the corridor being the last one.
- If none of the two first options are possible, then the mechanical ventilation rate is increased by 10 % (e.g. if it was 40 % of the maximum rate it becomes 50 % of the maximum rate).

And during this checking time, only one change at a time in the configuration of the room is allowed, i.e. that if the first test leads to a change it exits the process, and the same for the second one and so on. After a change has been made, the CO_2

concentration in the space is calculated again using the predictive model with the new configuration and again after the maximum value of the predicted CO_2 concentration has been compared to the limit. If the maximum is still higher than the limit, the same options are treated the same way as described before but conditions are added to the first and second one: the number of opened windows has to be less than the number of windows in the room and the same for the number of opened openings between neighboring rooms. After each new change, the CO_2 concentrations in the rooms are predicted with the calculation model. This loop ends when the maximum value in each room for the time period is lower than the limit or if the mechanical ventilation rates are at their maximum. Then the configuration of the space for the time period is considered as the optimal one and CO_2 concentration at the end of this period becomes the initial point of the next period in the control model. The same process is applied again for the next step, the ventilation configuration being settled back to the minimum for the new analyze.

This strategy has been implemented with Matlab scripts and then tested virtually with the space in Konetalo containing the two computer rooms K1242 and K1243, the lecture room K1241 next to the K1242, and the corridor along these three rooms. These rooms can be seen in the Figure 7-10 in the appendix E. The dimensions and maximum flow rates were the ones from the drawings of the buildings, the openings between the rooms and the corridor are the doors (2.05 x 0.8 m), and the openings between the rooms have all the same size to simplify (two times 0.4 x 1 m, one at the ceiling and one near the floor). The CO_2 limit concentration allowed in the rooms was settled to 1200 ppm which corresponds to the environment category III from the standard EN 15251 (800 ppm above the outdoor concentration which is about 400 ppm) and the outdoor minimum temperature to open the windows was 15 ºC.

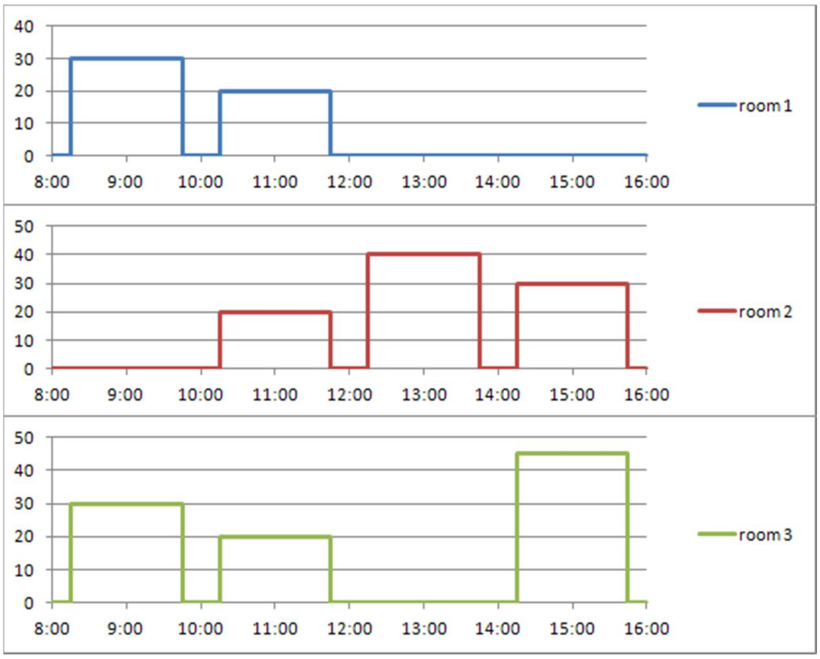

Figure 7-1 Occupancy of the three rooms for the control comparison

In order to give an idea of the potential savings that can be accomplished by using neighboring rooms' openings, a virtual example has been created for the occupancy of each room. The occupancy of each room is presented in the Figure 7-1. There are four lecture periods during the day, the duration of one lecture is 90 minutes, the beginning and ending times are respectively 15 past and 15 before the sharp time. The four situations are all different. First, two rooms with 30 students with the middle room empty, then 20 students in each of the three rooms, then the middle room has 40 students in it and the other rooms are empty, and in last case rooms 2 and 3 are occupied by 30 and 45 students and the room 1 is empty. The mechanical ventilation flow rates from three ventilation's strategies have been compared between them. The first is Constant Air Volume (CAV) which uses the same mechanical ventilation flow rates during the running period of the ventilation unit. The designed rates from the building's ventilation drawings given in the Table 7-1 are used here. The second is Variable Air Volume (VAV) which adjusts the mechanical ventilation flow rates of each room in order to keep the CO_2 concentration under the limit. The third is called here Variable Air Volume with Openings (VAV_OP) and uses the principle described before.

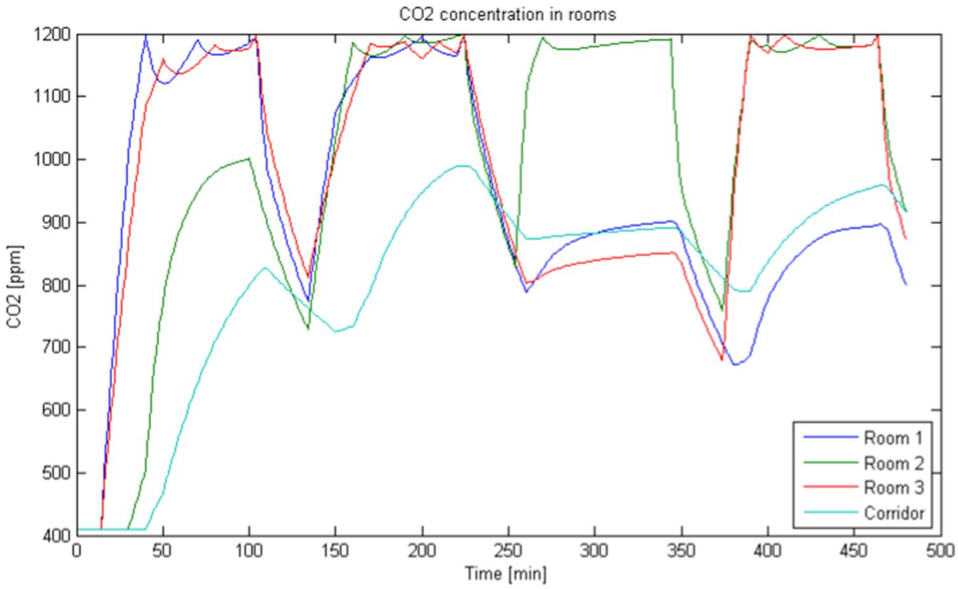

Figure 7-2 CO_2 concentration in the rooms with VAV_OP predictive control

The Figure 7-2 presents the CO_2 concentrations in the three rooms and in the corridor under the VAV_OP strategy for the control of the mechanical ventilation flow rates. The limit concentration of CO_2 is never exceeded in none of the rooms, the VAV_OP predictive control is thus working properly. The Figure 7-3 and the Figure 7-4 are showing respectively the evolution of the mechanical ventilation flow rates in each room and the status of the openings between the rooms. It is clear from these two graphs that when there are spaces with a low CO_2 concentration available next to an occupied room, using doors or gaps in the walls is offering the possibility to keep good air conditions without increasing the mechanical ventilation.

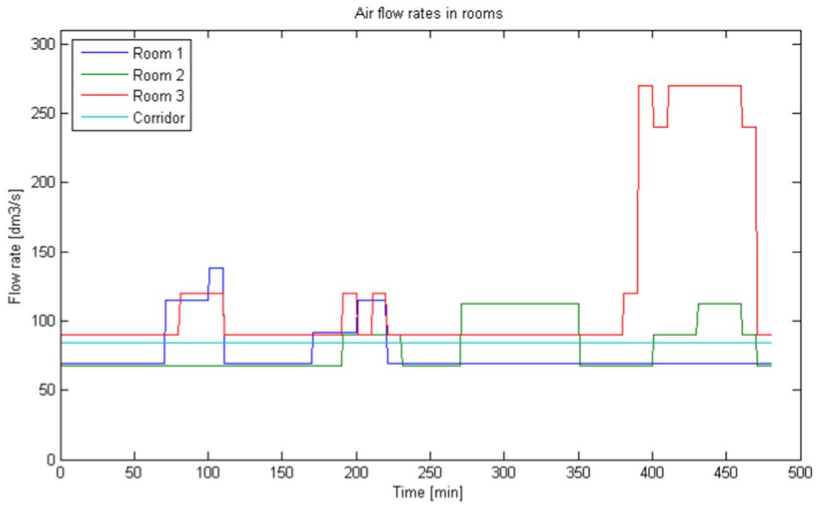

Figure 7-3 Mechanical ventilation flow rates with VAV_OP predictive control

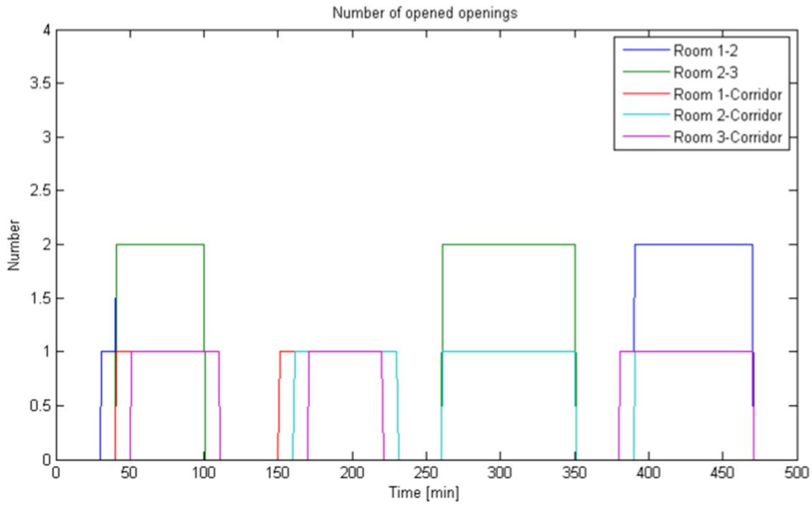

Figure 7-4 Neighboring rooms' openings status with VAV_OP predictive control

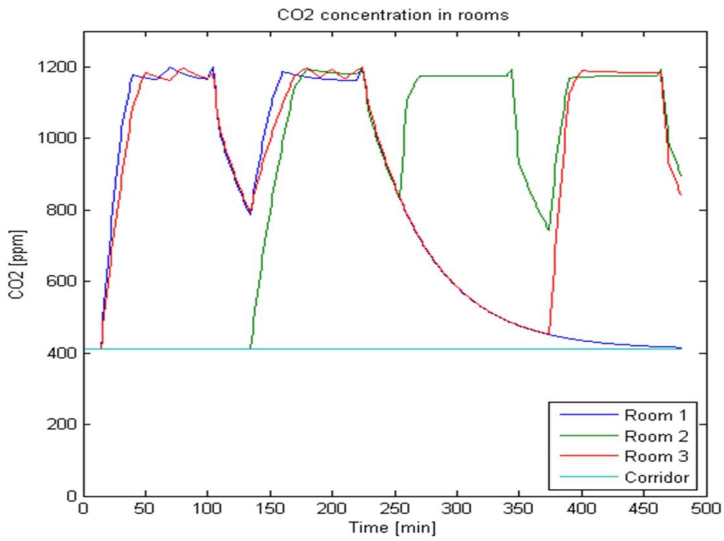

Figure 7-5 CO_2 concentration in the rooms with VAV predictive control

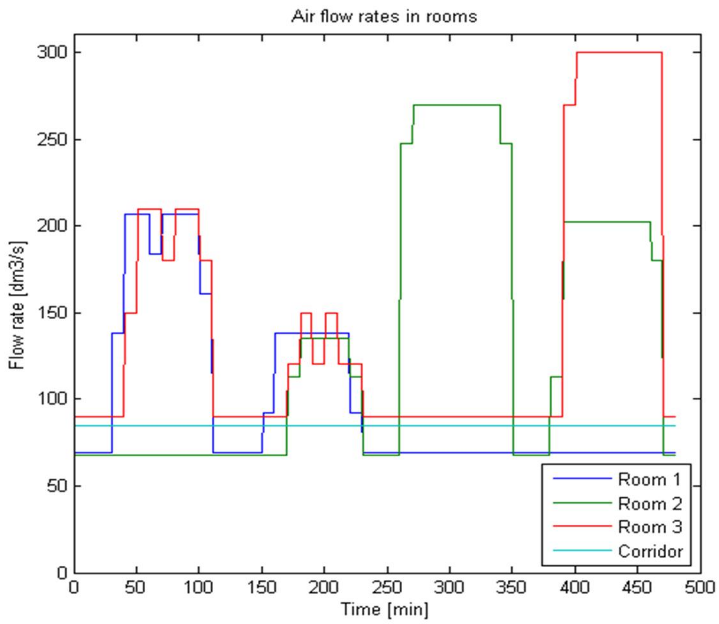

Figure 7-6 Mechanical ventilation flow rates with VAV predictive control

The Figure 7-5 presents the evolution of the CO_2 concentration in the rooms and in the corridor under the VAV predictive control. This strategy is also keeping the CO_2 concentration under the limit but compared to the Figure 7-2 the CO_2 concentration differences between the rooms are bigger. The Figure 7-6 shows the evolution of the mechanical ventilation flow rates under the VAV predictive control, and comparing those rates with those from the Figure 7-3 shows that the VAV_OP predictive control can significantly reduce the needs for mechanical ventilation.

Table 7-1 Savings from the mechanical ventilation flow rates with VAV and VAV_OP predictive control strategies compared to CAV.

Ventilation rates [dm^3/s]	Room 1	Room 2	Room 3	Corridor	Total
CAV	230,00	225,00	300,00	85,00	840,00
VAV (average value)	98,65	134,86	144,26	85,00	462,77
VAV_OP (average value)	76,65	81,53	122,43	85,00	365,61
Saving compare to CAV					
VAV	57 %	40 %	52 %	0 %	45 %
VAV_OP	67 %	64 %	59 %	0 %	56 %
Saving compare to VAV					
VAV_OP	22 %	40 %	15 %	0 %	21 %

The conclusion of this virtual simulation is summarized in the Table 7-1. It gives the savings of mechanical ventilation use under the VAV and VAV_OP strategies compared to the CAV. The use of VAV_OP control can reduce the need for mechanical ventilation by 56 % and 21 % compared respectively to CAV and VAV. Using the openings between the rooms is thus a potential source of energy saving. Nevertheless further analyze and longer tests period test have to be conducted to determine the real energy saving potential of the VAV_OP predictive control of the ventilation.

7.2. Conclusion

At the end of this study, after the different experiments and measurements have been conducted, the results of the work are leading to different conclusions and recommendations.

The conclusions can be distinguished in three points listed under.

Firstly, the predictive multi-room CO_2 model is now giving very good results compared to the measurements in many different real situations. The model is able to predict the CO_2 concentration in a room using variable occupancy, effect of opening windows, and effect of airflows between rooms or spaces via wall gaps or doors. The numerous different input parameters enable the model to cope with many different situations and/or configurations, in order to give an accurate forecast of the CO_2 situation in different rooms. The principle can easily be adapted or extended to different building configurations.

Secondly, the different measurement sessions in the rooms of the university, in addition to demonstrate the validity of the calculation model have highlighted some interesting results. Using an opening between two neighboring rooms has shown a significant effect on the CO_2 concentrations in both rooms. It can reduce the maximum CO_2 concentration in the occupied room when the other room is empty and it can accelerate of the speed CO_2 concentration drop during lecture breaks. Therefore the needs of mechanical ventilation could be reduced when such openings are available. The same conclusion can be made with the opening of windows when the outside temperature is warm enough. Moreover, using windows appeared to be a very efficient and easy way to keep low CO_2 concentrations in rooms.

Finally, the WIREPAS measurement system that has been used for all the experiments is a very easy and convenient solution for indoor conditions' monitoring. The wireless technology makes it easy to install and the data stored in an online database is accessible from the internet for the analysis. Combining this WIREPAS system with the predictive CO_2 model is offering possibilities to control the mechanical ventilation and the space configuration with potential energy savings, as the last part of the study started to highlight.

Nevertheless, some recommendations to further research this subject are presented now.

Going further in analyzing the discharge coefficient for the inside openings and the windows. This is a critical point for the rightness of the calculated CO_2 concentrations. Especially because the discharge coefficient affects significantly the efficiency of the openings between rooms, depending on their geometrical configuration.

To develop a control of the mechanical ventilation using the possibilities now offered by the predictive CO_2 model. This should establish a link between the measurement system, e.g. WIREPAS, the schedule of the different rooms and the predictive model.

Conduct a pilot test of the control of the mechanical ventilation with the predictive CO_2 model in order to determine better the energy saving potential of the strategy.

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Appendix A Indoor temperatures (EN 15251)

The Table 7-2 describes the temperature ranges the different type of building for three categories of indoor environment, as described in the part 3.1.2 Standard EN 15251. The temperature ranges are given for cooling during the cold season and for heating during the warm season with the assumption of adapted clothing[7].

Table 7-2 Temperature ranges for heating and cooling in three categories of indoor environment

Type of building or space	Category	Temperature range for heating, °C Clothing ~ 1,0 clo	Temperature range for cooling, °C Clothing ~ 0,5 clo
Residential buildings, living spaces (bed room's living rooms etc.) Sedentary activity ~1,2 met	I	21,0 -25,0	23,5 - 25,5
	II	**20,0-25,0**	**23,0 - 26,0**
	III	18,0- 25,0	22,0 - 27,0
Residential buildings, other spaces (kitchens, storages etc.) Standing-walking activity ~1,5 met	I	18,0-25,0	
	II	**16,0-25,0**	
	III	14,0-25,0	
Offices and spaces with similar activity (single offices, open plan offices, conference rooms, auditorium, cafeteria, restaurants, class rooms, Sedentary activity ~1,2 met	I	21,0 – 23,0	23,5 - 25,5
	II	**20,0 – 24,0**	**23,0 - 26,0**
	III	19,0 – 25,0	22,0 - 27,0
Kindergarten Standing-walking activity ~1,4 met	I	19,0 – 21,0	22,5 - 24,5
	II	**17,5 – 22,5**	**21,5 – 25,5**
	III	16,5 – 23,5	21,0 - 26,0
Department store Standing-walking activity ~1,6 met	I	17,5 – 20,5	22,0 - 24,0
	II	**16,0 – 22,0**	**21,0– 25,0**
	III	15,0 – 23,0	20,0 - 26,0

[7] Clothing is measured in clo is the unit to describe what a person is wearing in terms of insulation, thus 0 clo corresponds to a naked person, 1 clo corresponds to a person wearing a typical suit and 0.5 clo for light summer clothes. 1 clo = 0.155 m^2K/W

Appendix B Single room CO_2 model: Matlab scripts

In this appendix are presented the Matlab script for the comparison of analytical and numerical solutions of the single room CO_2 model.

```
clear all;clc;
%Comparison of analytical and numerical solutions of single room model

%-----------------------Description of the room-----------------------

L=9; %Length [m]
W=8; %Width [m]
H=3; %Height [m]
V=L*H*W*1000; %volume [dm3]

%------------------------------Occupants------------------------------

Np=25; %Number of person in the room
%Caracteristics of the person
run 'Human';

%Vco2 is the CO2 emission rate per person and comes from Human script
G=Np*Vco2; %[dm3/s]

%-----------------------------Ventilation-----------------------------

%CO2 concentration of outside air 10e-6.[ppm]
Co=410/1000000;
%CO2 concentration of inside air at t=0 10e-6.[ppm]
Ci=410/1000000;

%Mechanical airflow rate [dm3/s]
Q=180;
%Air change rate [s-1]
n=Q/V;

%------------------------CO2 room concentration-----------------------

%Duration [min]
tf=120;
tn= [0:2:tf];%vector for the numerical solution
t= [0:tf*60];%vector for the analytical solution

%Analytical solution
if(Q~=0)
    Ca = Co+G/Q+(Ci-Co-G/Q)*exp(-n*t);
else
    Ca = Ci+(G/V)*t;
end
```

```
%Numerical solution
imax=length(tn(1,:));
i=1;
%Allocation of a vector for CO2 level in the room
Cn=zeros(imax,1);

while(i<=imax)

if(i==1)
    Cn(i,1)=Ci;
else
    dt=(tn(i)-tn(i-1))*60;
    Cn(i,1)=Cn(i-1,1)+dt*(G/V+n*(Co-Cn(i-1,1)));
end
i=i+1;
end

%Display the result of the two solutions
plot(t/60,Ca*1000000,tn,Cn*1000000);
title('CO2 level in the room');
ylabel('CO2 [ppm]');
xlabel('Time [min]');
legend('Analytical solution','Numerical
solution','Location','SouthEast');
```

Programme B-7-1 Single room model: comparison's script

Appendix C Multi-room CO_2 model: Matlab scripts

In this appendix are presented the Matlab scripts for the comparison of the analytical solution approximated by the numerical algorithm “ode45” and the numerical solution by the finite difference method for multi-room space CO_2 concentration model.

```
clear all;clc;
%Comparison of analytical and numerical solutions for multiroom space
model

%-----------------------Description of rooms------------------------
%Size of rooms
L=9; %Length [m]
W=8; %Width [m]
H=3; %Height [m]
V=L*H*W*1000; %volume [dm3]
global V1;V1=V; %room 1
global V2;V2=V; %room 2
global V3;V3=V; %room 3

%Corridor
global Vc;
Vc=3*V; %equal to the sum of the volume of the three rooms

%-------------------Characteristics of occupants--------------------
%Number of person in room i
Np1=20;
Np2=5;
Np3=30;
Np=[Np1 Np2 Np3];

%From Human script the CO2 emission rate per person Vco2 is calculated
run 'Human';

%Production of carbon dioxide from occupants in room i [dm3/s]
global G1;G1=Vco2*Np1;
global G2;G2=Vco2*Np2;
global G3;G3=Vco2*Np3;

%--------------------------Ventilation------------------------------
global Co;
%CO2 concentration of outside air 10e-6.[ppm]
Co=410/1000000;
%CO2 concentration of inside air at t=0 in room i 10e-6.[ppm]
Ci1=410/1000000;
Ci2=410/1000000;
Ci3=410/1000000;
Cic=410/1000000;
Ci=[Ci1; Ci2; Ci3; Cic];

%Mechanical airflow rate in room i [dm3/s]
global Q1;Q1=150;
global Q2;Q2=150;
global Q3;Q3=150;
```

```
%Mechanical airflow rate in the corridor (from standard 0.35 dm3/s/m2)
global Qc;Qc=Vc*0.35/3000;
Q=[Q1 Q2 Q3 Qc];

%Air change rate in room i [s-1]
n1=Q1/V1;
n2=Q2/V2;
n3=Q3/V3;
nc=Qc/Vc;

%Average inside temperature in rooms [K]
T1=295;
T2=294;
T3=296;
Tc=294;

%Temperature differences
dT12=abs(T1-T2);
dT23=abs(T2-T3);
dT1c=abs(T1-Tc);
dT2c=abs(T2-Tc);
dT3c=abs(T3-Tc);

%Dimensions of the opening between room 1 and room 2
Hop=2; %Height [m]
Wop=1; %Width [m]
Aop=Hop*Wop; %Area [m2]

%Rate of air exchange between room i and j [dm3/s]
global Q12;Q12=opening_rate(Aop, Hop, (T1+T2)/2, dT12);
global Q23;Q23=0;

%Dimensions of doors between rooms and corridor
Hd=2; %Height [m]
Wd=0.8; %Width [m]
Ad=Hd*Wd; %Area [m2]

global Q1c;Q1c=0;
global Q2c;Q2c=0;
global Q3c;Q3c=opening_rate(Ad, Hd, (T3+Tc)/2, dT3c);

%Air flow rates between room i and j [dm3/s] and initial values
Qop=[Q12 Q23 Q1c Q2c Q3c];

%No windows opend
Qw=[0 0 0];

%----------------------CO2 concentration in rooms---------------------
%Duration [min]
tf=120;

%Analytical solution
%Solving the system
option=odeset('MaxStep', 120, 'Refine', 1);
[t, Ca] = ode45('diffC', [0 (tf*60)], Ci, option);

%Numerical solution
tn= [0:2:tf]; %time vector
Cn = rooms_CO2_concentration(Q, Ci, Np, Qop, Qw, tn);
```

```
%Calculate the absolute value of the difference of each point for the
two solutions and save the maximum difference di and the range Ii
[d1 I1]=max(abs(Ca(:,1)-Cn(:,1)));
[d2 I2]=max(abs(Ca(:,2)-Cn(:,2)));
[d3 I3]=max(abs(Ca(:,3)-Cn(:,3)));
[d4 I4]=max(abs(Ca(:,4)-Cn(:,4)));

%Maximal relative errors [%]
e1=abs((Ca(I1,1)-Cn(I1,1))/Ca(I1,1))*100
e2=abs((Ca(I2,1)-Cn(I2,1))/Ca(I2,1))*100
e3=abs((Ca(I3,1)-Cn(I3,1))/Ca(I3,1))*100
e4=abs((Ca(I4,1)-Cn(I4,1))/Ca(I4,1))*100

%Display the evolution of CO2 concentration in rooms as function of
time
subplot(2,2,1);plot(t/60,Ca(:,1)*1000000,tn,Cn(:,1)*1000000);
title('CO2 level of room 1');
ylabel('CO2 [ppm]');
xlabel('Time [min]');
legend('Analytical','Numerical','Location','SouthEast');

subplot(2,2,2);plot(t/60,Ca(:,2)*1000000,tn,Cn(:,2)*1000000);
title('CO2 level of room 2');
ylabel('CO2 [ppm]');
xlabel('Time [min]');
legend('Analytical','Numerical','Location','SouthEast');

subplot(2,2,3);plot(t/60,Ca(:,3)*1000000,tn,Cn(:,3)*1000000);
title('CO2 level of room 3');
ylabel('CO2 [ppm]');
xlabel('Time [min]');
legend('Analytical','Numerical','Location','SouthEast');

subplot(2,2,4);plot(t/60,Ca(:,4)*1000000,tn,Cn(:,4)*1000000);
title('CO2 level of corridor');
ylabel('CO2 [ppm]');
xlabel('Time [min]');
legend('Analytical','Numerical','Location','SouthEast');
```

Programme C-1 Multi-room model: comparison’s script

```
function [Qop] = opening_rate(A, H, Tin, dT)

%Calculates the flow rates through the openings with the inputs:
%the area of the opening A [m2]
%the height or maximum difference between the lowest point and the
highest
%point of the opening H
%the temperature inside Tin
%the temperature difference through the opening dT

%standard gravity [m/s2]
g=9.81;

%Flow rate through the opening [m3/s]
Qop=(A/3)*(g*H*dT/Tin)^0.5;

%converted in [dm3/s]
Qop=Qop*1000;

End
```

Programme C-2 Script of the function ‘opening_rate’

```
function dC = diffC(t, C)

% Defines the differential equations from the vector C and gives them
% in the vector dC

%Definition of the component functions of the vector C
C1=C(1);
C2=C(2);
C3=C(3);
Cc=C(4);

%Outside variables
global Q1;global Q2;global Q3;global Qc;
global Q12;global Q23;
global Q1c;global Q2c;global Q3c;
global V1;global V2;global V3;global Vc;
global G1;global G2;global G3;global Co;

%Differential equations
dC1=-(Q1+Q12+Q1c)*C1/V1+(Q12/V1)*C2+(Q1c/V1)*Cc+(Q1*Co+G1)/V1;
dC2=-(Q2+Q12+Q23+Q2c)*C2/V2+(Q12/V2)*C1+(Q23/V2)*C3+(Q2c/V2)*Cc+
(Q2*Co+G2)/V2;
dC3=-(Q3+Q23+Q3c)*C3/V3+(Q23/V3)*C2+(Q3c/V3)*Cc+(Q3*Co+G3)/V3;
dCc=-(Qc+Q1c+Q2c+Q3c)*Cc/Vc+(Q1c/Vc)*C1+(Q2c/Vc)*C2+(Q3c/Vc)*C3+
(Qc*Co)/Vc;

%Derivated vector dC
dC=[dC1; dC2; dC3; dCc];

end
```

Programme C-3 Script of the function ‘diifC’

```
function [ C ] = rooms_CO2_concentration( Q, Ci, Np, Qop, Qw, t )

%Calculates the CO2 concentration in the room during the period of the
%length t minutes, the inputs are:
%the mechanical flow rates in the rooms: vector Q
%the initial concentrations in the rooms: vector Ci
%the occupancy of the rooms: Vector Np
%the flow rates from the inside openings: vector Qop
%the flow rates from windows: vector Qw

%Variables
%Volume of the rooms
global V1;global V2;global V3;global Vc;
%CO2 emisions per occupant
global Vco2;
%Outside air CO2 concentrations
global Co;

%Definition of the components of the vector Q
Q1=Q(1);
Q2=Q(2);
Q3=Q(3);
Qc=Q(4);

Q12=Qop(1);
Q23=Qop(2);
Q1c=Qop(3);
Q2c=Qop(4);
Q3c=Qop(5);

%If there are windows opened the airflow is added to the room airflow
Q1tot=Q1+Qw(1);
Q2tot=Q2+Qw(2);
Q3tot=Q3+Qw(3);

%Air change rate in room i [s-1]
n1=Q1tot/V1;
n2=Q2tot/V2;
n3=Q3tot/V3;
nc=Qc/Vc;

%Production of CO2 from occupants in room i [dm3/s]
G1=Vco2*Np(1);
G2=Vco2*Np(2);
G3=Vco2*Np(3);

%Loop which calculates CO2 concentrations step by step

dt=(t(2)-t(1))*60; %the time step is 60s
imax=length(t); %the number of steps for the time vector

%Allocation of vectors for CO2 level in rooms
C1=zeros(imax,1);
C2=zeros(imax,1);
C3=zeros(imax,1);
Cc=zeros(imax,1);
```

```
i=1;
while(i<=imax)
if(i==1)
    C1(i)=Ci(1);
    C2(i)=Ci(2);
    C3(i)=Ci(3);
    Cc(i)=Ci(4);
else
    %Room 1
    %CO2 leaving the room
    C1out=n1*C1(i-1)+((Q12+Q1c)/V1)*C1(i-1);
    %CO2 entering the room
    C1in=G1/V1+n1*Co+(Q12/V1)*C2(i-1)+(Q1c/V1)*Cc(i-1);
    %CO2 level
    C1(i)=C1(i-1)+dt*(C1in-C1out);

    %Room 2
    C2out=n2*C2(i-1)+((Q12+Q23+Q2c)/V2)*C2(i-1);
    C2in=G2/V2+n2*Co+ (Q12/V2)*C1(i-1)+(Q23/V2)*C3(i-1)+
(Q2c/V2)*Cc(i-1);
    C2(i)=C2(i-1)+dt*(C2in-C2out);

    %Room 3
    C3out=n3*C3(i-1)+((Q23+Q3c)/V3)*C3(i-1);
    C3in=G3/V3+n3*Co+(Q23/V3)*C2(i-1)+(Q3c/V3)*Cc(i-1);
    C3(i)=C3(i-1)+dt*(C3in-C3out);

    %Corridor
    Ccout=nc*Cc(i-1)+((Q1c+Q2c+Q3c)/Vc)*Cc(i-1);
    Ccin=nc*Co+(Q1c/Vc)*C1(i-1)+(Q2c/Vc)*C2(i-1)+(Q3c/Vc)*C3(i-1);
    Cc(i)=Cc(i-1)+dt*(Ccin-Ccout);
end
i=i+1;
end

%the output: matrix with all the concentrations in each room
C=[C1 C2 C3 Cc];

end
```

Programme C-4 Script of the function ‘rooms_CO2_concentration’

Appendix D Excel interface for the predictive CO_2 model

In order to use the calculation methods described in the thesis text and compare the theoretical model with the measurements. The step by step numerical solution being relatively simple to implement and Excel is offering a user friendly interface which is quite well known by everyone. It is also a good solution for an input/output interface of the CO_2 model. Moreover, the Visual Basic module for Macros' creation enables to make the calculation using only one Excel WorkBook. This Excel WorkBook is taking as basic structure the three rooms and one corridor space presented on Figure 5-4. Each room has its own sheet containing all the specific inputs and the CO_2 concentration over the time period as raw data and chart, one sheet for the neighboring room openings, one for people characteristics, and temp storage sheets for calculation raw data.

In each room's sheet of which Figure 7-7 is giving an overview, in the blue part on the left from the top the table asks to fill in room's size, mechanical ventilation air flow rate, CO_2 concentration of supply air and in room's initial configuration, then the window's characteristics, and the temperatures. The window's part is giving the situation for one window, i.e. the effective opened area, discharge coefficient, pressure difference through the window, and the calculated corresponding air flow from the equation 5-30. The second part on the right in green is asking the occupancy of the room every ten minutes along the day (from 8 a.m. to 6 p.m.), also the number of opened windows and the status of the neighboring rooms openings. This status represented here by a number is acting as a coefficient multiplied to all the exchange flow rates of this room with the other neighboring rooms (indicated in the left part with ventilation settings). This enables to include for example the opening of a door only during part of the day, and also eventually with this door only half opened or the opening of two doors at the same time while using the same air exchange value as reference for this opening. Then on the right side are the results of the calculation, first the CO_2 concentration every ten minutes with the single room CO_2 model (numerical finite difference method), and second the CO_2 concentration every ten minutes for the multi-room space CO_2 model (numerical finite difference method). The calculation for each model is made when pressing one of the two buttons "Update Single Room" and "Update Multi-Room"; they are running the Macro script containing the equations of each model. The description of the openings between neighboring rooms is on a different WorkSheet. The left part of Figure 7-8 shows an example for the opening between room 1 and room 2. This table asks all the parameters required to calculate the flow through the opening (equation 5-29), i.e. the height, the width, the temperature difference and the temperature in the room. Each of the other possible openings has the same table. The last WorkSheet contains the characteristics of people and gives the CO_2 emission rate per person; it is shown on the right side of Figure 7-8. The tables require the average height and weight, the respiratory quotient, and the metabolic rate to calculate the CO_2 emission rate with the equation 4-4.

Room dimensions		
Width	5,95	m
Depth	7,05	m
Height	3,05	m
Volume	**127,9399**	**m^3**
Ventilation settings		
Fresh air rate	**78**	**L/s**
Air exchange with room 1	0	L/s
Air exchange with room 2	0	L/s
Air exchange with corridor	151,8065	L/s
CO2 level of fresh air	**410**	**ppm**
CO2 initial level	**410**	**ppm**
Windows		
Height	1,3	m
How open	0,15	m
Area	0,195	m2
Discharge coefficient	0,67	
Density of air	1,2	kg/m3
Pressure difference	2	Pa
Air flow	**238,5332**	**dm3/s**
Temperature		
Outside Temperature	3	°C
Inside temperature	24	°C
Temperature difference	21	°C

Update Single room

Update Multi room

Schedule		Number of opened windows	Openings	Single room	Multi room
Time	Occupancy			CO2 level (ppm)	CO2 level (ppm)
8:00	0	0	0	410,00	410,00
8:10	0	0	0	410,00	410,00
8:20	0	0	0	410,00	410,00
8:30	0	0	0	410,00	410,00
8:40	0	0	0	410,00	410,00
8:50	0	0	0	410,00	410,00
9:00	1	0	0	423,29	423,29
9:10	1	0	0	439,79	439,79
9:20	4	0	0	491,02	491,02
9:30	4	0	0	548,35	548,35
9:40	4	0	0	587,85	587,85
9:50	4	0	0	615,06	615,06
10:00	4	0	0	633,80	633,80
10:10	0	0	0	593,56	593,56
10:20	0	0	0	536,45	536,45
10:30	0	0	0	497,11	497,11
10:40	0	0	0	470,01	470,01
10:50	0	0	0	451,34	451,34
11:00	0	0	0	438,48	438,48
11:10	0	0	0	429,62	429,62
11:20	0	0	0	423,52	423,52
11:30	0	0	0	419,31	419,31
11:40	0	0	0	416,41	416,41
11:50	0	0	0	414,42	414,42
12:00	0	0	0	413,04	413,04
12:10	0	0	1	412,10	411,42
12:20	8	0	1	517,76	501,05
12:30	10	0	1	675,89	600,00
12:40	10	0	1	799,51	664,65
12:50	10	0	1	884,68	709,99
13:00	10	0	1	943,35	745,76
13:10	10	0	1	983,76	774,94
13:20	9	0	1	998,32	787,65
13:30	9	0	1	1001,00	797,87
13:40	9	0	1	1002,85	808,49
13:50	9	0	1	1004,12	817,71
14:00	9	0	1	1005,00	825,40
14:10	0	0	0	886,00	744,33
14:20	5	0	0	804,36	706,76
14:30	5	0	0	784,85	717,61

Figure 7-7 Room's sheet: input and output data

Room 1 - Room 2		
Heigh	1,7	m
Width	1,2	m
Surface of opening	2,04	m^2
Temperature difference	0,5	K
Temperature in room	295	K
Flow rate	114,33	dm^3/s

People		
Mean Height	1,73	m
Mean Weight	68,2	kg
DuBois Area	1,81	m^2
Respiratory quotient	0,83	
Metabolic rate	1,2	met
CO2 emission rate	**5,17E-03**	**dm^3/s**

Figure 7-8 Description of a neighboring rooms' opening and its airflow (left) and description of room's occupants and their CO_2 emission rate per person (right)

Appendix E Konetalo

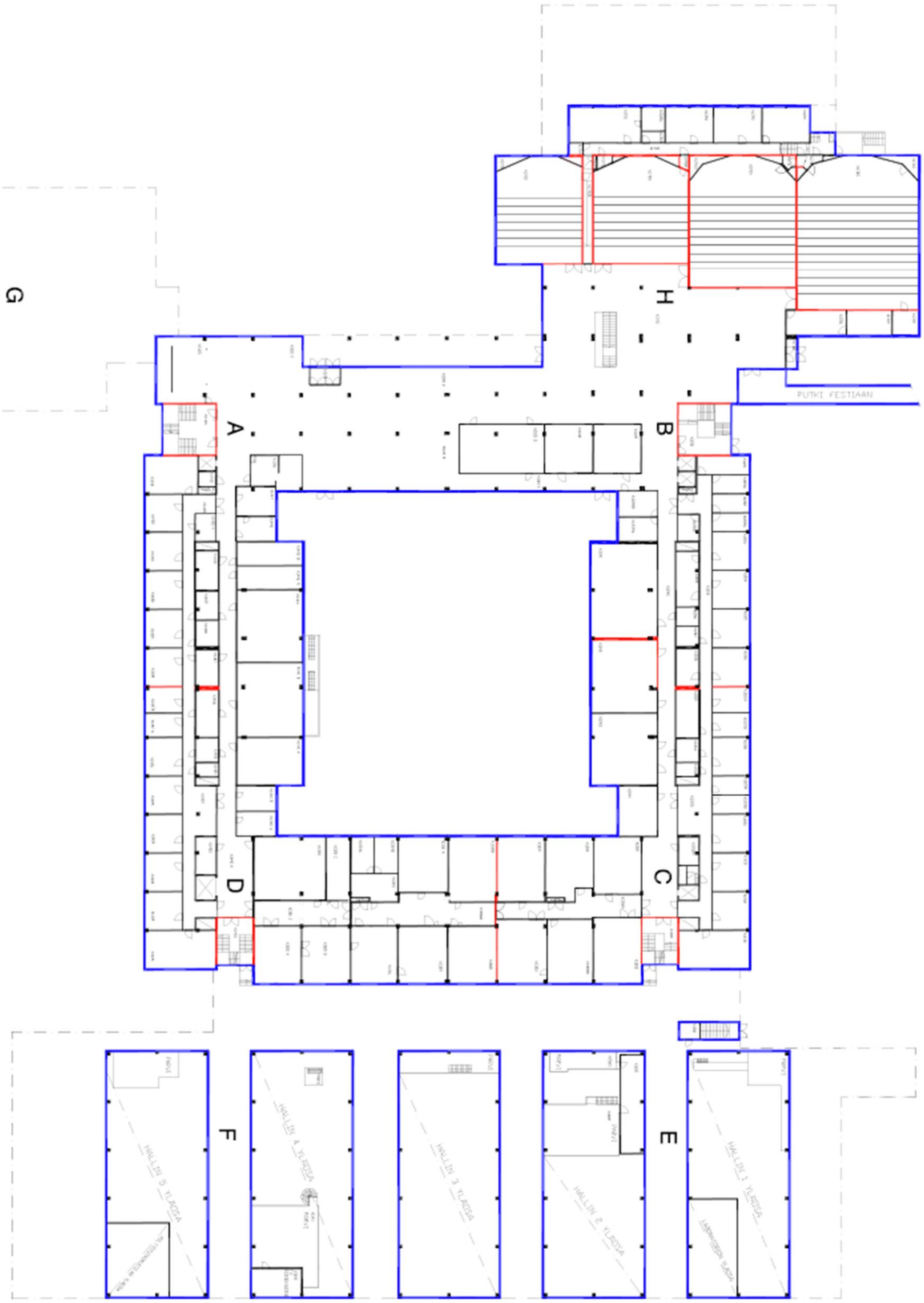


Figure 7-9 Rooms of Konetalo’s first floor

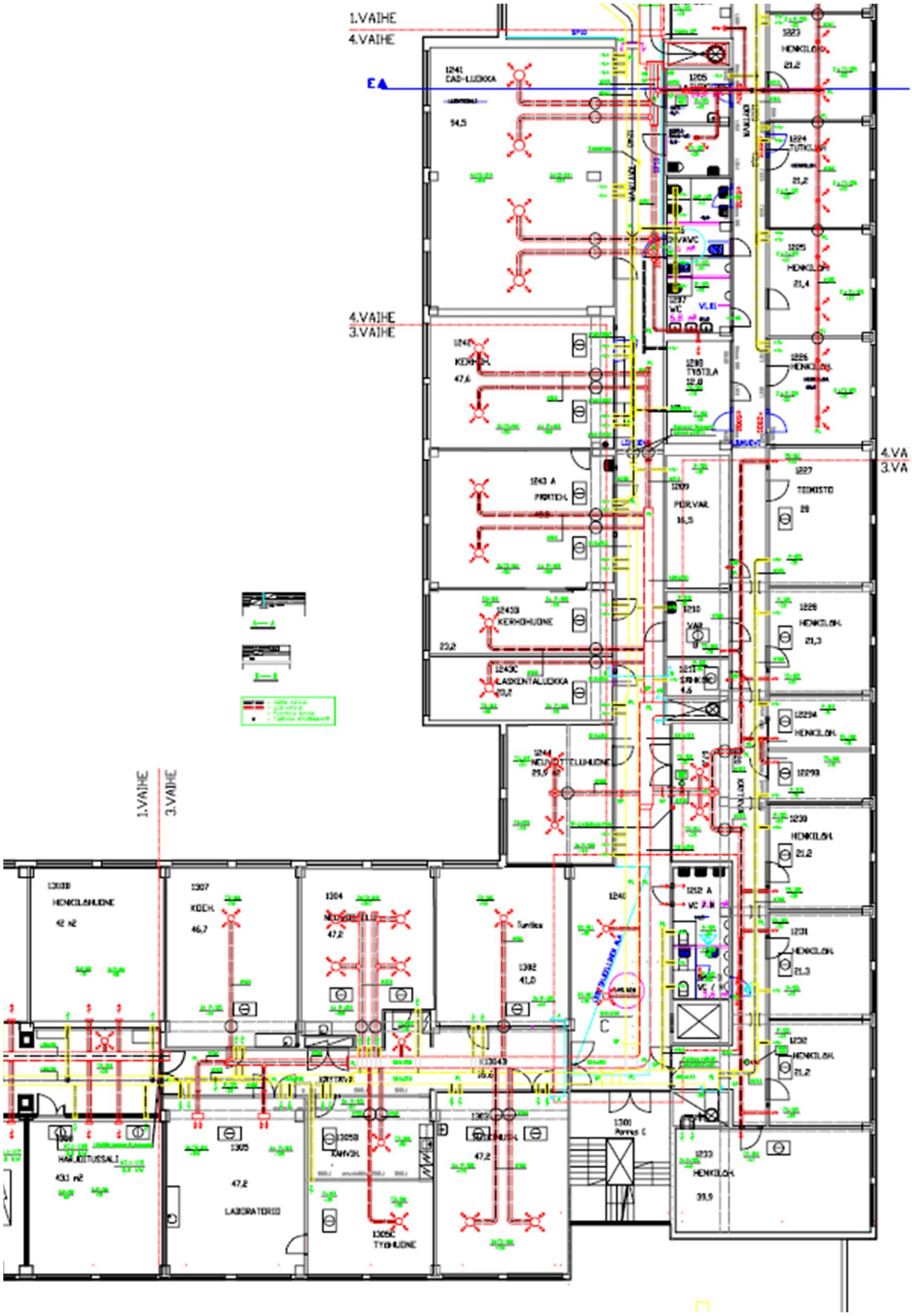
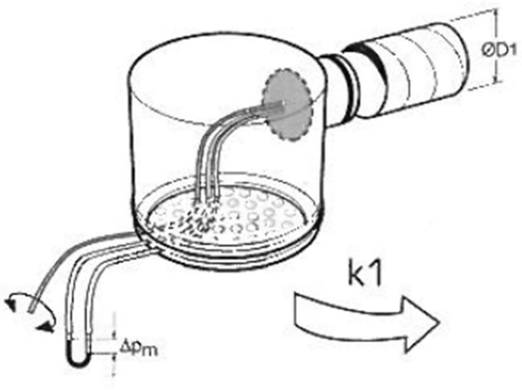


Figure 7-10 View of the ventilation circuits of the department of Mechanics and Design (part of the first floor of Konetalo)

Appendix F Ventilation vents documentation

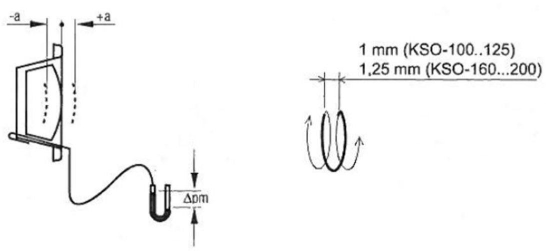
CYLP, CYLO



	DTTZ 09.1996 lähtien	ATTA 03.2001 lähtien	ATTA 03.2003 lähtien
ØD1	k1	k1	k1
100	7,4	7,4	7,4
125	13,0	13,0	13,0
160	25,3	21,5	15,9
200	38,0	36,0	24,5
250	63,5	63,5	37,7
315	97,0	97,0	64,8

Figure 7-11 Table of the coefficient k for the supply vents CYLP

KSO, KSO-P, KSO-V+DBL



KSO-100 a	k
-15	0,5
-12	0,8
-10	1,0
-5	1,4
0	1,9
5	2,3
10	2,8

KSO-125 a	k
-10	1,5
-5	2,1
0	2,7
5	3,3
10	4,0

KSO-160 a	k
-10	2,0
-5	2,8
0	3,6
5	4,4
10	5,3
15	6,2

KSO-200 a	k
-3	1,8
0	2,4
5	3,8
10	5,0
15	6,3
20	7,5
25	8,6

Figure 7-12 Table of the coefficient k for the exhaust vents KSO

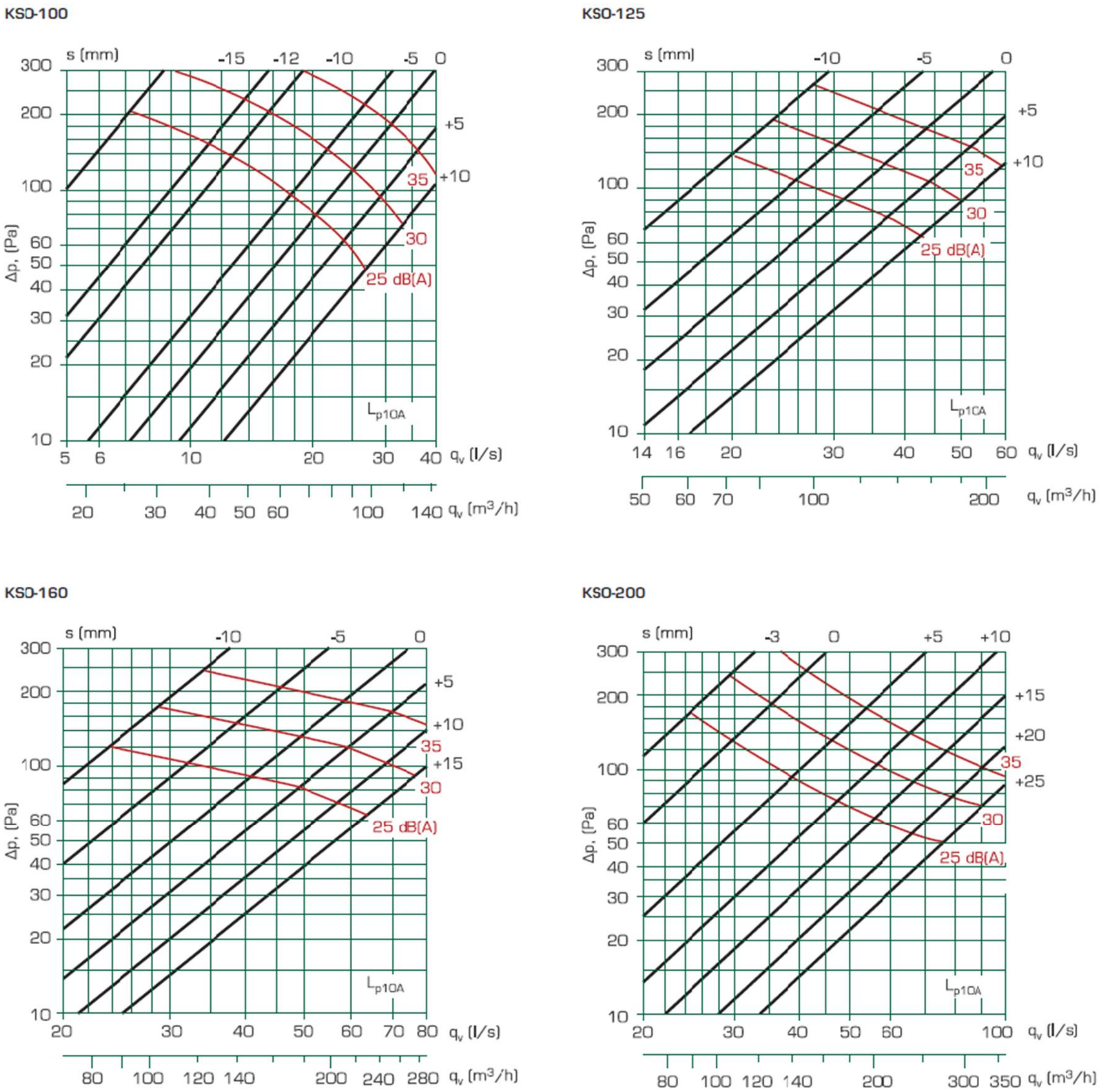


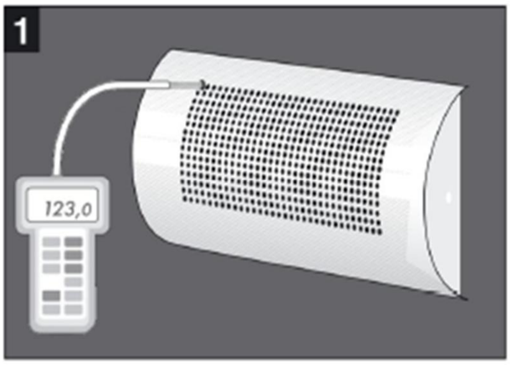
Figure 7-13 Flow rates characteristics charts for the exhaust vents KSO

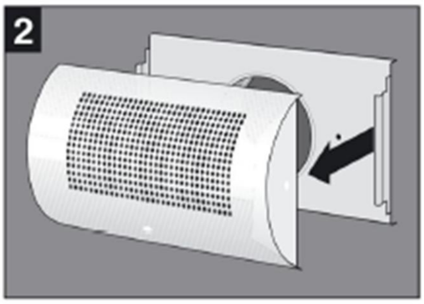
OKE

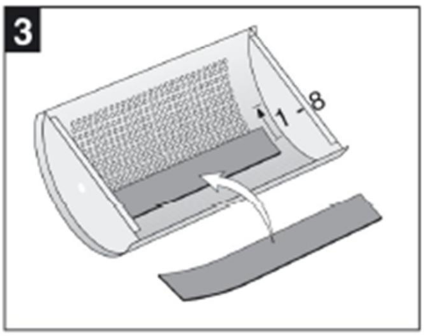
$$q_v = k \times \sqrt{\Delta p_m}$$

		k			
OKE		**100**	**125**	**160**	**200**
		9*20	12*24	15*32	19*38
A		3,6	6,1	10,8	15,2
Suljettu riviä / Stängda / Closed rows	1	3,2	5,6	9,9	14,3
	2	2,8	5,0	9,0	13,4
	3	2,4	4,5	8,2	12,5
	4	2,0	4,0	7,3	11,6
	5	1,6	3,5	6,6	10,8
	6	1,2	2,9	5,9	10,0
	7		2,4	5,2	9,1
	8			4,4	8,3

Huom! Ei koske OKE-P:tä
Obs! Gäller ej OKE-P
Attention! Does not concern OKE-P







Poistoilma
Frånluft
Exhaust air

OKE	100	125	160	200
A	3,5	5,6	9,4	14,1

Figure 7-14 Flow rate determination for supply vents OKE

Appendix G Measurement systems

G.1 WIREPAS: wireless measurement system

The WIREPAS measurement and documentation system has initially been developed at the Tampere University of Technology and is now available on the market from the WIREPAS Company. This technology is used by a few departments of the university, including the department of Mechanics and Design. The WIREPAS system was used for collecting data from different spaces in the building such as computer rooms, lecture rooms, corridors and offices.

Figure 7-15 Wirepas nodes

The WIREPAS system is a wireless sensor solution, examples of the sensors are in the Figure 7-15. It is composed of battery or generic voltage supplied sensors measuring things such as humidity, inside or outside temperature, motion detection (activity), carbon dioxide level, luminance, acceleration/orientation/chock, air velocity, noise level, heat (pulse input), voltage, electric current, electric resistance, electricity consumption, water consumption, door or window switch, and structure and soil moisture. The system requires having a gateway connected to any internet access (GPRS/3G, Ethernet, ADSL) and it builds its own network, each sensor becoming a node by which signals are transferred to the central server. All measurements are available in real time and anywhere with an internet connection and correct identification to the WIREPAS interface.

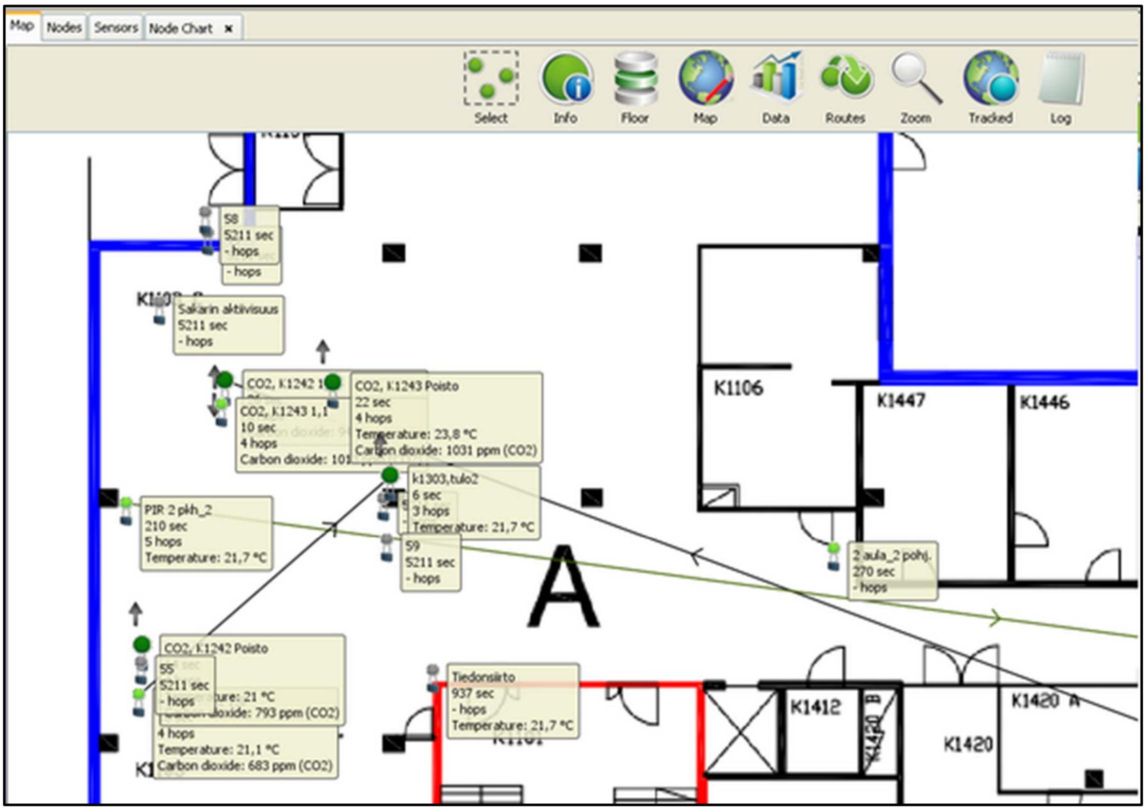


Figure 7-16 Wirepas Control Panel: Node's map

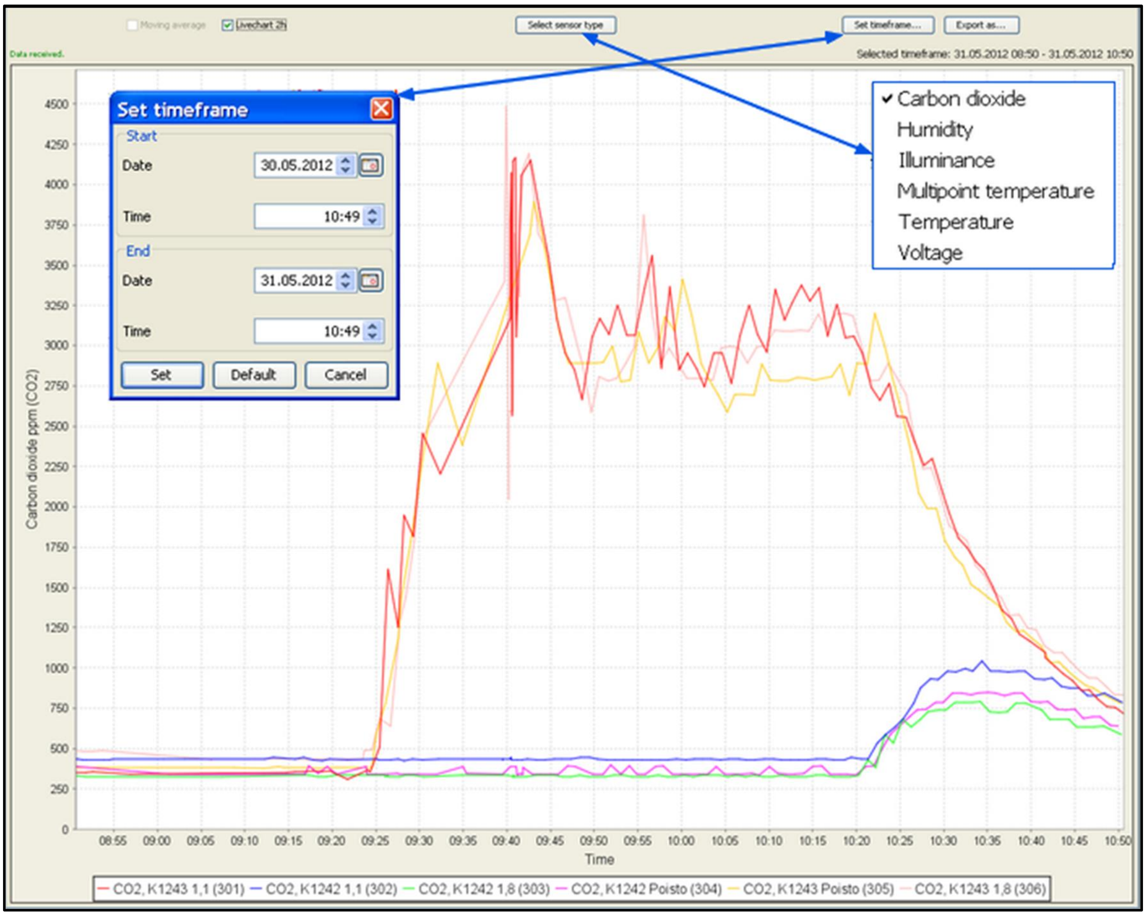


Figure 7-17 Wirepas Control Panel: Node chart

The WIREPAS interface uses Java web started application '*WIREPAS Control Panel*', also available for mobile phone. With the control panel, the user can organize his sensors, area by area and a map can be introduced in the background, as can be seen in the Figure 7-16 (Entrance hall of Konetalo). The measured values from the sensors can be read directly on the map or in the node list tab. And the sensors' values can be plotted on a chart to have a graphic overview of a real time monitoring. This node chart is illustrated in the Figure 7-17, on the main part is the two hours' real time monitoring for CO_2 sensors. A button gives the possibility for the user to select the time period (day and time) for the selected nodes, and another button allows choosing the data which is plotted (CO_2, temperature…). Other options enable to get a moving average to get curves smoother, and data can be exported to PDF file as a picture of the chart or to a table in an excel file for further analysis.

(Wirepas Oy, 2010)

G.2 Other measurement devices

In order to measure the rates of the mechanical ventilation, pressure difference through openings, punctual CO_2 concentration, air flows, or temperature some hand devices have been used. They can be seen in the Figure 7-18:

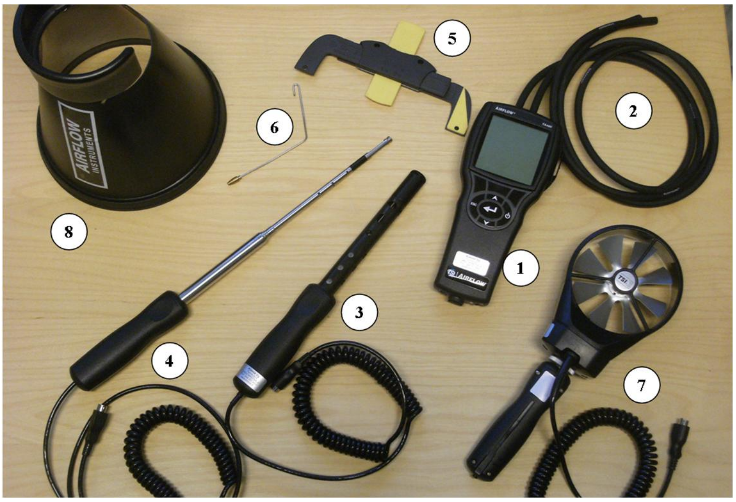


Figure 7-18 Hand measurement devices

1- Main device which plot the measured values for plug extension (2, 3, 4, 7), and measure pressure difference, barometer pressure, and pitot velocity
2- Pressure difference pipes
3- Stick for CO_2 concentration, temperature, humidity, dew point, and wet bulb
4- Extensible stick for air velocity, temperature, humidity, dew point, and wet bulb
5- Specific tool to know the adjustment of the exhaust vents
6- Specific pipe to combine with one of the pipes (2) to get the pressure difference through the exhaust vents
7- Measures the air velocity, and airflow with the fan, and gives the temperature
8- Cylinder used with the fan (7) to measure airflow or air velocity for a vent